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PREFACE

This document was prepared in response to the “JUXOCO Assessment of Explosive Specific Detection Technologies” task for the Deputy Undersecretary of Defense (Science and Technology) (DUSD(S&T)) and in behalf of the Joint UXO Coordination Office (JUXOCO), the Under Secretary of Defense (Acquisition, Technology, and Logistics (USD(AT&L), the Director, Defense Research and Engineering (DDR&E), and the Deputy Assistant Secretary of the Army (Environment, Safety, and Occupational Health) (DASA(ESOH)). Technical cognizance for this task order is assigned to Dr. Hermann Spitzer (JUXOCO). The DUSD(S&T) point of contact (POC) is Mr. Howard J. Taylor, and the Institute for Defense Analyses (IDA) POC is Dr. David Heberlein.

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EXECUTIVE SUMMARY

The detection of buried land mines and unexploded ordnance (UXO) is a challenge for the technical community. Most military and commercial detectors use electromagnetic induction (EMI) to sense the presence of metal casings or components in mines and UXO. Some of the newer detectors also incorporate ground-penetrating radar (GPR) for target acquisition. The difficulty with these technologies is that they also detect buried anomalies and are, therefore, prone to high false alarm levels. Explosive components are common to all buried mines and military ordnance and, therefore, offer a unique discriminator among other buried objects.

Two approaches for detecting buried explosives are chemical trace detection and radiation techniques.

1. **Chemical trace detection.** This approach relies on detecting either the vapor emanating from the buried devices or the small explosive particles [and/or explosive related compounds (ERCs)] concentrated in the top portion of the soil. The amount of explosive available for detection ranges from nothing to small (micrograms per liter) amounts that vary considerably with type of buried device, the type of soil, the amount of water present in the soil, and the weather. The transport of the chemicals through soils is a complex process that can involve changes of phase, interactions with the soil, and biochemical reactions. Therefore, even the most capable chemical detection equipment cannot provide robust detection in all environments and scenarios. Also, the time required for trace detection technologies to indicate the presence of explosives or ERCs ranges from seconds to several minutes. As a result, none of the trace detection technologies are suitable for use as a scanning sensor. Trace detection techniques function best when combined with sensors that can rapidly scan areas to identify potential target locations. Over 20 chemical trace detection technologies are discussed in this report. In some cases, two or more of these technical approaches can be combined into a single system to provide greater specificity or sensitivity. The most mature and prevalent approaches are different forms of ion mobility spectrometry (IMS), preconcentrators and gas chromatography (GC).
2. **Radiation techniques.** This approach uses radiation to probe beneath the earth's surface to provide bulk detection of buried explosive devices. Both electromagnetic and neutron radiation techniques can be used to detect buried

explosive ordnance. Radiation techniques are generally limited to the detection of shallowly buried objects (i.e., objects buried within 10–20 cm of the earth’s surface). While neutrons can be used for greater penetration depths than 10–20 cm, the number of false alarms increases as the depth increases. With the exception of lateral scanning x-ray migration technology [lateral migration radiography (LMR)], the radiation approaches discussed in this report require several seconds to minutes to achieve explosive detection. Therefore, radiation techniques also need to be combined with scanning sensors that identify buried target locations. The most promising approaches appear to be LMR, nuclear quadrupole resonance (NQR), and pulsed fast-neutron analysis (PFNA). At this time, all three approaches have been demonstrated in the field and can detect buried explosive mines and UXO within 10 cm of the earth’s surface.

The success of chemical trace detection depends on how much of the explosive particles or explosive vapors are available at the earth’s surface. To assist in the detection of explosives below the earth’s surface, transport codes have been developed by the Army’s Engineer Research and Development Center (ERDC), Sandia National Laboratories (SNL), and other groups to describe the movement of explosive particles, ERCs, and their vapors through soil. These models consider vapor-solid partitioning, vapor-liquid partitioning, soil vapor diffusion, soil particle size, sorption, microbial degradation, plant root uptake, precipitation, evaporation, and liquid diffusion. The fundamental issue is to describe the time history of the evolution of explosive material as it comes to the surface. Because the number and quality of field measurements of explosive materials’ transport in soils is limited, using transport models to estimate the variances that can be observed in field measurements is important.

The concentration of explosives, ERCs, and explosive vapors changes in time and depends on the amount of water, the weather, and the different types of soil. Thus, different environments present different opportunities for chemical trace detection. For example, sandy environments with moderate rainfall present reasonable detection opportunities within days or weeks after explosives are buried but are of limited value years later. On the other hand, dry clay environments may require months to years before detectable amounts of explosives, ERCs, and their vapors are available for detection. Despite the incredible sensitivities claimed by the proponents of existing and emerging chemical trace detection technologies, using trace-gas detection when either high explosive backgrounds are present or when no surface trace gases or solids are present is an exercise in futility. Chemical trace detection technologies need to be viewed for providing “niche”

roles in explosive detection for countermine, explosive ordnance disposal (EOD), humanitarian demining, munitions response, and range sustainment. Generally, these niche roles use chemical detection to provide other detectors with information about the possible presence of trace explosives.

Similarly, radiation techniques used to detect bulk explosives can be fused with other detection technologies that have the ability to scan and identify buried explosives rapidly. NQR has recently been fused with the U. S. Army AN/PSS-14 mine detector, which uses both EMI and GPR to detect buried mines. The NQR can only be used to detect explosives cased in plastic and wood. While most neutron radiation technologies require bulky equipment, a much lighter PFNA technique marketed as pulsed elemental analysis with neutrons (PELAN) has demonstrated the ability to detect shallowly buried antitank (AT) mines. The neutron-based detectors are being used in EOD scenarios to discriminate explosive field shells and ordnance from empty casings.

JUXOCO needs to play a leadership role in establishing standards for reporting the results of field measurements in which chemical trace analyses are used for the detection of buried mines and ordnance. Many reports provide anecdotal information as opposed to providing the results of serious data collection. Currently, chemical trace detections are reported from tests in which no specific information exists on either the background levels or the amounts of explosives/ERCs for which detection was reported. As a minimum, the JUXOCO should specify acceptable instruments (e.g., some form of IMS) for measurements of both background and point-of-detection/sampling. In addition, JUXOCO should specify acceptable sources to calibrate the IMS instruments. At the site maintained by JUXOCO, performing background measurements at several locations within the site at periodic intervals would also be helpful. The background measurements would be useful for planning future tests and for determining the advantages and disadvantages of new technologies as they are field tested.

I. INTRODUCTION

Historically, for buried mine and unexploded ordnance (UXO) detection, the goal has been the direct detection of the device's explosive component(s). Chemical, nuclear, and electromagnetic techniques have been used to detect explosives directly, but a robust approach for detecting all types of mines and UXO in a variety of environments has never been demonstrated. The objective of this report is to provide an overview and an assessment of direct explosive detection approaches that could be used for countermine operations, explosive ordnance disposal (EOD), humanitarian demining, munitions response, and range sustainment. Chemical trace detection and radiation systems are discussed with regard to their ability to find and identify Improvised Explosive Devices (IEDs).

This intent of this report is to provide the Joint Unexploded Ordnance Coordination Office (JUXOCO) a reference document that can help future researchers establish programs to exploit direct explosive detection technologies. To achieve these objectives, it provides the following information:

- A parametric model approach to describe the amount and types of explosives and explosive-related compounds (ERCs)¹ that could be available for detection in a variety of environments
- A description and evaluation of the current explosive vapor detection technologies
- A description and evaluation of the current explosive trace particle detection technologies
- A description and evaluation of the current nuclear and x-ray chemical detection technologies, including that of current Nuclear Quadrupole Resonance (NQR) techniques to detect plastic mines or buried explosives

¹ A short time after a land mine is buried, explosives (such as trinitrotoluene, TNT) or major explosive contaminants (such as dinitrobenzene, DNB) begin to leak into the surrounding soil. These explosives/explosive contaminants leach toward the surface, usually undergoing chemical or biological transformation into other mixes called ERCs (explosive-related compounds).
(Source: <http://engineering.jhu.edu/~cmsd/REMPL/>)

- Niche roles that explosive detection technologies could fill in countermine, EOD, humanitarian demining, munitions response, and range sustainment.

The following assumptions were made in considering the different candidate technologies and targets:

- Explosives of interest are limited to military explosives (TNT, RDX, HMX and PETN) and their ERCs (2,4 TNT, DNT, and 2,4-DNT).
- The targets should not have been moved (i.e., the target must be detected in situ).
- All technologies considered should have the potential to become field mobile even though they may now be laboratory techniques.

Many of the technologies discussed in this report are emerging as candidates for future field use. The sensitivities of many of these candidate technologies are given by the developer and are noted as such. An attempt has been made to cite the data source so that the reader can judge its applicability to his or her specific interest.

In general, calibrated data from field measurements are difficult to make and to find. While other field measurements may exist, we cite the vapor measurement data of Jenkins and Kjellstrom (see Table II-1) and the solid-trace measurement data of Chambers, Desilets, Phelan and Webb, Jenkins, and Kjellstrom (see Table II-2). We also cite these measurements to evaluate our model results in Section II.

II. CHEMICAL DETECTION

A. BACKGROUND

Buried explosive compounds can be detected through emitted vapors or through traces of microscopic solid particles (often on the order of a few micrograms). Most chemical detection technologies rely on gas phase and decomposition techniques. Spot sampling is a time-consuming but critical process. Sample collection is generally done by hand.

Gas samples are gathered with gas collection equipment, and different hardware is then used for sample preparation and analyses. Several different types of vapor traps are used: volume traps (charcoal); surface or membrane traps, and solid plate surfaces.

Microparticles can be collected through mechanical agitation, swabbing, vibration, and thermal desorption. The rate of detection ranges from several seconds to minutes and is even longer when the sample collection process is considered a part of the detection process.

Unfortunately, the available testing data are rarely comparable. To exacerbate the situation, the performance of many detection systems is hindered by the lack of background data and the “actual” or mass spectrographic amount of explosive available for detection.

1. Explosive Vapor Detection

The amount of surface vapor is affected by burial depth, soil type, and the amount of water in the soil. Generally, vapor concentrations are highest over sandy soils, less over silty soils, and least over clay soils. To complicate matters, the efficiencies necessary for vapor collection and trapping further reduce the amounts of explosive vapor available for evaluation or detection.

Most explosives have a low equilibrium vapor concentration. The room-temperature equilibrium vapor concentration is 9 parts per billion (ppb)² for TNT, 0.006 ppb for RDX, and 0.0001 ppb for HMX. The equilibrium vapor concentration of some ERCs, such as DNT, is higher than that of TNT and is frequently the principal target for detection. Plastic explosives exhibit even lower equilibrium vapor concentrations than pure explosive compounds. The equilibrium vapor concentration decreases an order of magnitude when the temperature drops from 23°C to 4°C.

The method by which the mine or UXO device is encapsulated determines how much—if any—explosive vapor may be available for detection. In general, explosive vapors can diffuse through plastic and wood enclosures, which provide a long-term source of explosive vapor that can rise to the earth's surface. However, metal-enclosed UXOs do not permit vapor diffusion into the surrounding soil, and the only explosive available for transport through the soil is the residual explosive particles remaining on the surface of the UXO from manufacture, handling, or storage. Therefore, for metal-enclosed UXOs, it is difficult to determine how much explosive—if any—would be available for transport to the earth's surface. The wide range of expected values for the availability of explosive vapors (and for solid explosive particles) limits the robustness of chemical detection techniques.³

2. Explosive Trace Particle Detection

Residual explosive particles left on the surfaces of mines and UXO are one source for the transport of solid explosives through a soil. Cracked and open land mines and UXO are another source for the subsurface transport of solid explosive particles. Because the explosive compounds change as they move to the surface, ERCs are more prevalent than the original explosive compounds. Time, distance from the source, and soil moisture and type affect the concentration of explosives and ERCs in the soil and on the earth's surface. In the late 1990s, the U.S. Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC)⁴ and Sandia National Laboratory (SNL) were

² One part in 10⁹.

³ Chemical sensors must be used with other types of sensors to ensure reasonable probabilities of detection.

⁴ Through the ERDC's Cold Regions Research and Engineering Laboratory (CRREL) and ERDC's Environmental Laboratory.

involved in developing codes to predict explosive transport and in conducting measurements of transport phenomena.

The contamination in and around buried explosive devices evolves in time into an area that can contain the original explosive microparticles, different ERC microparticles, and the equilibrium vapor associated with each explosive compound. Of these compounds, 2,4-DNT has much greater environmental stability than TNT and 1,3-DNB. The ERCs are transported by water and temperature (as a function of time) through the soil surrounding the mine or UXO. ERCs are often found in a discontinuous halo around the perimeter of mines and UXO.

A far greater amount of explosive is available for detection in solid explosive microparticles and their ERCs than is available in explosive vapors. One milliliter of vapors contains less than one millionth the mass explosive signature of one gram of contaminated soil. The values given in the literature ranged from 2–877 ng/g for TNT and 5–5,400 ng/g for 2,4-DNT [ng/g = nanograms (of explosive) per gram (of soil)]. The greater source of explosive available for detection only suggests the presence of a buried explosive device but does not necessarily pinpoint the position of the device. In tests conducted by Jenkins et al. (Ref. 1) at Ft. Leonard Wood, Missouri, the ERCs were measured in and around different mine types.

B. TRANSPORT MODELS

Several groups have developed computer codes to calculate the transport of explosive chemicals through percolation, diffusion, and convection⁵ from the source at depth to the surface of the ground. These groups include Jury et al. (Refs. 2, 3, 4), R. Mayer et al. (Ref. 5), Phelan et al. (Refs. 6, 7), and Padilla et al. (Refs. 8, 9). The models consider vapor-solid partitioning, vapor-liquid partitioning, soil vapor diffusion, soil particle size, sorption, microbial degradation, plant root uptake, precipitation, evaporation, and liquid diffusion.

The fundamental issue is to describe the time history of the evolution of explosive material as it comes to the surface. Because the number and quality of field measurements of explosive materials' transport in soils is limited, using transport models to

⁵ Percolation concerns the movement and filtering of fluids through porous materials; diffusion refers to the process by which molecules intermingle as a result of their kinetic energy of random motion; and convection is the flow of heat through a bulk, macroscopic movement of matter from a hot region to a cool region.

estimate the variances that can be observed in field measurements is important. Available codes generally require the support of their developer.

Because the available resources for this task were limited, an Institute for Defense Analyses (IDA) code was developed. This code was based on the physics and chemistry described by Phelan et al. (Ref. 6) and Jury et al. (Refs. 2, 3). The IDA code is included in Appendix A.

1. Code

The code developed by IDA is an adaptation of a heat-transfer code developed earlier. It was modified to include other phenomena of interest, such as water flow. The IDA Soil Diffusion Program includes the following phenomena:

- Inhomogeneous soil properties (different materials in different regions of interest)
- Source: bulk explosive or flux in region
- Diffusion of explosive in soil
- Water convection in soil
- Deterioration of explosive through chemical reaction
- Sorption to soil and vaporization into air layer
- Transfer of explosive between phases.

To treat diffusion, the similarity of the heat equation and diffusion equation made necessary only adjustments in the coefficients to generate early runs. The equations and necessary coefficients were found in various papers, including those by Jury et al. (Refs. 2, 3, 4), Phelan et al. (Ref. 6). The current IDA code is written in FORTRAN and is two-dimensional (2-D), but it can easily be generalized into three dimensions. The FORTRAN code does not have a plotting routine; therefore, to help visualize the output, additional code in MATLAB has been written to generate graphs.

2. Transport of Explosives in the Ground Using Finite Element Simulation (FES)

The processes controlling the concentration of explosive molecules in the ground fall into two categories: transformation and transport. In detail the processes are many and complex. They stem from chemical reactions, molecular diffusion, heating, flow of underground water, evaporation of water, saturation of soil from rain water, vaporization, sorption, and decomposition of explosives.

A three-dimensional (3-D) simulation technique is developed to describe the concentration distribution of explosives in the ground and above the ground for various soils, weather conditions and scenarios, including leakage assumptions. As a first step toward a more comprehensive capability in three dimensions, we discuss the general procedure and then apply it to a one-dimensional (1-D) problem. Generalization to two and three dimensions is straightforward.

The computational procedure adopted is FES (Refs. 10, 11). The FES technique relies on the application of physical and chemical laws, usually in a linearized version, to the system under investigation.

The system is divided into several convenient cells (labeled i,j,k), and each cell is characterized by three types of parameters:

1. Geometrical parameters $\zeta(i)$, such as the position of the center of a cell, its volume, cross-sectional area, surface area, and so forth
2. Physical parameters $\rho(i)$, such as diffusivity, specific heat, flow velocity, and so forth
3. Transport functions $\tau(i)$, such as temperature, concentration (s), and so forth.

$\tau(i)$ is an intensive parameter, and the associated extensive parameters, (e.g., heat, number of particles) are denoted $Q(i)$. The parameters in the transport functions group are specified, initially, $\tau(i)$ at $t = 0$, and a time interval, Δt , is chosen over which the calculation is to take place. The choice of Δt is governed by the requirement that it should be small enough to prevent “overshoot” in the calculations, which could lead to instability and unphysical results. This is a well-known condition that is invoked to prevent numerical problems. Basically, this condition prevents transfer of more than the amount of material available in a cell to another cell, a danger in a linearized simulation.

The heart of the calculation is the set of physical laws that describe changes in the system parameters $\tau(i)$ over the time interval $(t, t + \Delta t)$. A general process (m) can be thought of as causing a change, $\Delta Q^m(i)$, because of the transfer parameter, $\tau^m(i)$, of cell i . It can be calculated from

$$\Delta Q^m(i) = \Omega(i, i+1) \cdot \Lambda(i, i+1) \cdot \Phi(i, i+1) \Delta t, \quad (1)$$

where Ω , Λ , and Φ are functions of the appropriate geometrical, physical, and transfer parameters of the system.

$\Delta Q^m(i)$ is a change in the extensive parameter corresponding to $\tau^m(i)$ and gives the amount of “material” transferred out of cell (i) by the process m . In the case of molecular

diffusion, ΔQ is the number of molecules transported in time Δt because of the concentration differences in the cells. The changes in the transport functions can be obtained from

$$\Delta \tau^m(i) = (\Delta Q^m(i-1) - \Delta Q^m(i)) / R^m(i), \quad (2)$$

where $R^m(i)$ is a conversion factor between τ and Q (volume for molecular diffusion; the product of volume, mass, density, and specific heat for heat transfer).

Equation (2) leads to a new $\tau(i)$ at time $t + \Delta t$, which is obtained from all the $\Delta \tau^m(i)$ by

$$\tau(i)_{\text{new}} = \tau(i)_{\text{old}} + \sum_{m=1}^M \Delta \tau^m(i), \quad (3)$$

where we have assigned (M) independent processes affecting the parameter $\tau(i)$.

The preceding three steps are repeated until t_{max} is reached. The result of the calculation is a profile of the τ parameter as a function of position (cell center) for different times. This is a dynamic simulation calculation. Thus, to obtain an equilibrium situation, the temporal development has to be simulated until an asymptotic behavior is reached.

1-D Diffusion

Figure I-1 represents the simple geometry we have adopted for the problem of vertical diffusion of explosive molecules in the soil ($0 \leq Z \leq 80$ cm). The geometric parameters are cell dimensions l_i , positions $Z(i)$, separation of cell centers $\Delta Z(i-1, i)$ and volume V_i . For simplicity, we assume that the horizontal cross-sectional area of the cells $A(Z) = A = \text{constant}$. The physical parameters are the diffusivity, D_i , of a cell or the effective diffusivity between cells, $D(i, i-1)$. The transport parameters are the concentration, C_i , the number of particles, N_i , and the changes in these quantities transferred between cells, for example, $\Delta N(i-1, i)$.

The number of molecules transferred by diffusion from cell $(i-1)$ to cell (i) during the time interval Δt is given by

$$\Delta N(i-1, i) = \frac{-AD(i-1, i)}{\Delta Z(i-1, i)} [C(i) - C(i-1)] \cdot \Delta t, \quad (4)$$

where $C(i)$ is the concentration of the diffusing species in cell i and $\Delta Z(i-1, i) = Z(i) - Z(i-1)$ is the separation of centers of cells, i , and $i-1$. For cell i , the quantity $\Delta N(i-1, i)$ is positive if the particle flux is into the cell. Note that the diffusivity is the effective diffusivity defined as

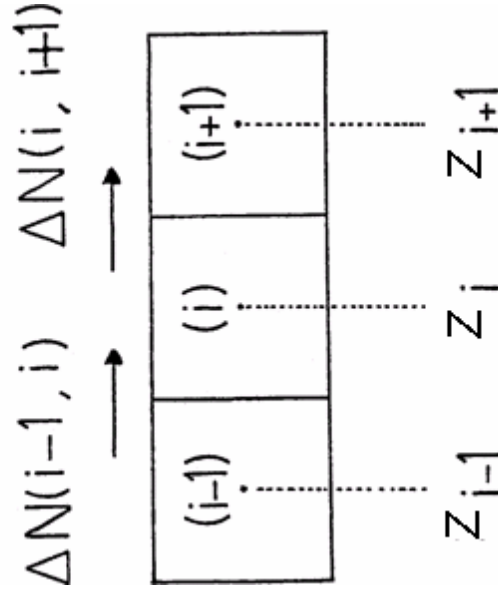


Figure I-1. Cell Geometry for 1-D Vertical Diffusion

$$D(i-1, i) = \frac{l_i + l_{i-1}}{l_i/D_i + l_{i-1}/D_{i-1}}, \quad (5)$$

where l_i is the length of the i^{th} cell.

Analytically, this expression can be written as a flux from one cell into the other and is dependent on the gradient between the two cells. Defining a flux into a cell as positive is done as follows:

$$F = -D \frac{dC}{dZ}, \quad (6)$$

where D is again the diffusion coefficient and F is the number of particles crossing a unit area per unit time between the interface of the two cells. The concentration change in the i^{th} cell after diffusive transfer between it and the two adjacent cells, $i-1$ and $i+1$, is

$$\Delta C_i^D = [\Delta N^D(i-1, i) - \Delta N^D(i, i+1)] \cdot \frac{1}{V_i}, \quad (7)$$

where $V(i)$ is the volume of the i^{th} cell. This is a special case of Eq. (2), where the parameter $R^m(i)$ is simply the volume of the i^{th} cell. The new concentration at time $t+\Delta t$ is

$$C_i(t + \Delta t) = C_i(t) + \Delta C_i^D. \quad (8)$$

This operation is performed for all the N cells in the system and is repeated n times for subsequent time intervals until the maximum required time $t_{\text{max}} = n\Delta t$ is reached. The calculation step (Δt) need not remain constant over the entire t_{max} time span but could be

changed as the calculation evolves. The result of the calculation is a “concentration profile” of the system as a function of time.

We can now show the correspondence between this approach and the diffusion equation. Consider the simple case of a homogeneous medium. The concentration change over the time interval, Δt , as calculated from Eqs. (4) and (7) can be written as

$$\frac{\Delta C_i(t, \Delta t)}{\Delta t} = D \cdot \frac{A}{\Delta Z_i} [C_{i-1} + C_{i+1} - 2C_i] \cdot \frac{1}{V_i}, \quad (9)$$

where $V_i = A \cdot \Delta Z_i$ is the volume of cell i and all cells are assumed to have identical cross-sectional areas and linear dimensions. Changing notations to $C_i \rightarrow C(Z)$, $C_{i-1} \rightarrow C(Z - \Delta Z)$, and $C_{i+1} \rightarrow C(Z + \Delta Z)$ and taking the limit as $\Delta t \rightarrow 0$ and $\Delta Z \rightarrow 0$ independently, we get

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial Z^2} \quad (10)$$

by the definition of the derivative. We have thus derived the diffusion equation from our two equations of transport in a homogeneous medium.

The next step in building up our simulation of the transport phenomena is to introduce the force field drift term (ΔC_i^F), which, in our case of molecular diffusion, arises from the water flow. Given an effective drift velocity, G'_i , between cells (caused, in this case, by the water flow), the number of molecules transferred from cell (i) to cell ($i + 1$) in the time Δt is given by

$$\Delta N^F(i, i+1) + G'(i, i+1) \frac{V_i}{\Delta Z_i} C_i \Delta t, \quad (11)$$

where $G(i + 1, i)$ is calculated the same way as $D(i + 1, i)$ (see Eq. 5). The change in the concentration of cell i because of this process is

$$\Delta C_i^F = [\Delta N^F(i-1, i) - \Delta N^F(i, i+1)] \cdot \frac{1}{V_i}. \quad (12)$$

Analytically, this change is usually referred to as the “advection term” in the continuity equation for concentration (C). It gives the time rate of change in C caused by drifting spatial gradients in C , that is,

$$\frac{\partial C}{\partial t} = \bar{v} \cdot \nabla C = v \frac{\partial C}{\partial Z}. \quad (13)$$

Following the procedure used with the diffusive term in Eq. (10), we can show that Eqs. (1), (2), (5), (11), and (12), in the appropriate limit, can be used to derive Smoluchowski's equation for diffusion in a force field for a homogeneous medium:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial Z^2} + G \frac{\partial C}{\partial Z}. \quad (14)$$

Finally, for reactive substances, we introduce the change in concentration caused by chemical reactions. Suppose the diffusing substance reacts with a background constituent whose concentration in cell i is given by C_i^b . The change in concentration of C_i because of the reactions of the diffusing material during the time interval, Δt , is given by

$$\Delta C_i^R = -k C_i \cdot C_i^b \Delta t, \quad (15)$$

where k is the chemical reaction rate in units of volume/time.

In summary, if C_i^α represents the concentration of substance α ($\alpha = 1, \dots, n_\alpha$) in cell i , then the total change in concentration is obtained from

$$\Delta C_i^\alpha(t, \Delta t) = \Delta C_i^D + \Delta C_i^F + \Delta C_i^R, \quad (16)$$

where the superscripts D, F, and R refer to diffusion, drift velocity in a force field, and reaction, respectively. We can apply a modified version of the reaction Eq. (15) to treat sorption, adsorption, decay of material vaporization, and so forth.

3. Measured Values and Model Predictions

Table II-1 shows experimental measurements of the TNT and DNT vapor found above different mine types and bare explosives buried in the ground. The IDA code predictions ranged from 0.00001–0.1 ng/L depending on the flux of explosive vapor assumed.

Table II-2 gives the soil measurements of solid particulates of TNT, DNT and 2,4-DNT.

The maximum values in Tables II-1 and II-2 indicate the large variability of explosive (or ERC) concentrations available at the earth's surface. Because the data presented represent only certain types of mixes in specific environments, the codes give an indication of the spectrum of explosive concentrations that may be available for detection.

Table II-1. TNT and DNT Vapor Measurements of Buried Mines and Buried Bare Explosives

| Source | Target Type | Explosive | Max Value (ng/L) |
|---|------------------------------------|----------------|----------------------|
| Jenkins (Ref. 1) (Ft. Leonard Wood/ silt loam soil) | TMA5 land mine | TNT 2,4-DNT | 0.00009 0.1500 |
| | PMA1A land mine | TNT 2,4-DNT | 0.00009 0.3000 |
| | Exposed TNT | 2,4-DNT | 0.4200 |
| Kjellstrom (Ref. 12) (Bosnia-Herzegovina/ wet soil) | 1g pressed TNT – magnetite in sand | TNT 2,4-DNT | Not reported 0.42 |
| | 1g pressed TNT – empty can w/TNT | TNT 2,4-DNT | Not reported 117 |
| Summary | | TNT 2,4-DNT | 0.00009 0.15–117 |

Table II-2. Field Measurements of Explosives and ERCs in Soil

| Source | Target Type | Explosive | Max Value (ng/g) |
|---|------------------------|----------------|------------------|
| Chambers (Ref. 13) (Soil data not available) | TM62 anti-vehicle mine | TNT DNT | 2,030 < 10* |
| Desilets (Ref. 14) (Soil data not available) | UXO | TNT | 2 to > 8 |
| Phelan and Webb (Ref. 15) (Kaho'olawe Island/dry soil) | 155 mm | TNT 2,4-DNT | 7–13 3 |
| | 100 # bomb | 2,4-DNT TNT | 36–631 20–877 |
| | 5" rocket, (1) | TNT | 5–32 |
| | 5" rocket, (2) | 2,4-DNT TNT | 9–97 20–586 |
| | 5" rocket, (3) | TNT | 9–68 |
| Jenkins (Ref. 1) (Ft. Leonard Wood/ silt loam soil) | TMA5 land mine | TNT 2,4-DNT | 44 248 |
| | PMA-1A land mine | TNT 2,4-DNT | 2 227 |
| Kjellstrom (Ref. 12) (Bosnia-Herzegovina/ wet soil) | PMA2 land mine | TNT | 720 |
| | TMA4 land mine | TNT | 96 |
| | TMA4 land mine | TNT | 160 |
| | PMA2 land mine | 2,4-DNT | 110 |
| | TMA4 land mine | 2,4-DNT | 380 |
| | TMA4 land mine | 2,4-DNT | 5,400 |
| Summary | | TNT 2,4-DNT | 2–877 5–5,400 |

The values for the IDA code ranged from 0.5–500 ng/g, depending on the assumed flux. The large range in the vapor and solid particulate measurements clearly indicates the wide range of possible results that can occur when chemical detection systems are used in the field. Even though sensors may have adequate sensitivity to detect specific types of explosive vapors and solid particulates in the laboratory, the large range in explosive residue (vapor or solid particulate) available for detection will drive probability of detection in all types of scenarios. The development of codes to predict transport can be used parametrically to portray the range of possible results that could emerge in different environments for different types of targets.

Figure II-1 shows the explosive concentration calculated by the IDA code in the air layer above a buried explosive. Figure II-2 shows the calculated change in concentration of explosives in the soil as a function of time. Figure II-1 clearly shows the migration that can occur over time as the explosives and ERCs move through the soil to the surface. In general, codes only begin to emulate the extremes in measured explosive amounts that have been noted in the literature from field measurements.

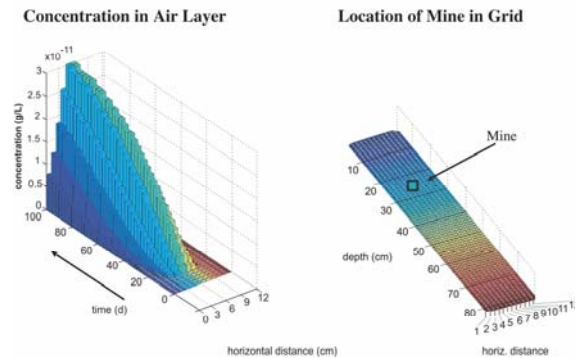


Figure II-1. Concentration of Explosives in the Air Layer Above the Target

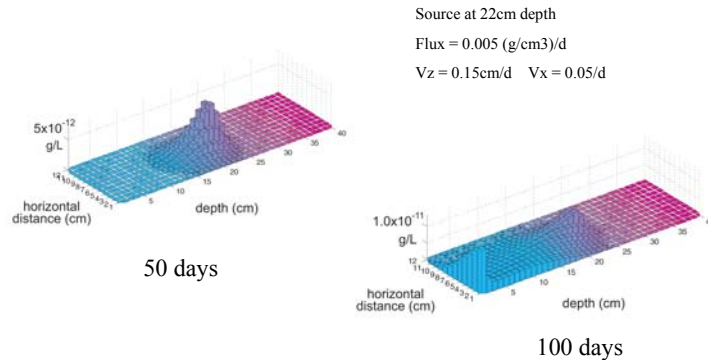


Figure II-2. Concentration of Explosives in the Soil

Weather and environmental variations, combined with the ideal parameterization used in code predictions, exacerbate the differences between code predictions and actual measurements. Modeling codes clearly point to the wide variations that can be expected in available explosive vapor or solid particulates. This wide variation has broad implications for using chemical trace approaches to locate buried explosives and explosive ordnance. For example:

- The explosives might not be buried at the exact point where vapor or soil samples are taken.
- The spread of the explosive and ERCs will require that multiple samples be taken to define the possible area of contamination.
- Anecdotal reports of mine detection using different technology approaches might reflect detections only where high amounts of explosive or ERCs are present.
- Mine detection using high-sensitivity trace explosive detection in highly contaminated areas could result in high false alarm rates.
- The length of time the explosive ordnance or fractured ordnance has been buried strongly affects the amounts of explosive or ERCs available for detection.
- The amount of ground water and rainfall affects the amount of explosive available for detection and the best times to obtain detection.
- Not all mines or ordnance leak or diffuse explosives. Trace detection will never be robust in the sense that every buried explosive or explosive device can be found.
- The measurement of explosive vapors may provide a more direct approach for finding the position of a buried device than the measurement of explosively contaminated soil (even though the density of explosive in the soil is much higher than that in the air).
- The use of calibrated explosive sources⁶ to verify the sensitivity of all trace technologies used in detection is strongly suggested. For different technology approaches to be useful, quantifying what and how much was detected in different field applications is important.

⁶ The response of each detector should be known for specific explosives and ERCs.

C. TECHNOLOGY APPROACHES/CAPABILITIES

Table II-3 shows a large variety of chemical vapor and solid particulate explosive detection technologies, together with the “claimed” capability of each technology approach against a spectrum of explosives applicable for this effort. Table II-3 is intended to be a quick-reference chart to determine which technologies look promising against specific explosives.

Appendix B has a data sheet for each technology approach listed in Table II-3. These data sheets give a brief description of each technology, sensitivity (if available), measurement time, size and portability, maturity, affordability issues, and reliability/false alarms issues. The data sheets also include a brief background and description of each technology, known technical issues, and specific citations and references. Appendix B can be used with Table II-3 to gain additional information on each technology approach.

1. General

A large number of chemical trace detection techniques are being applied to the detection of explosives. However, this report is concerned with detection of explosives and explosive devices that are buried in the soil, and the trace chemical detection techniques used by the Department of Homeland Security (DHS) to detect explosives on transportation passengers and baggage may not be appropriate or capable of finding buried explosives and explosive devices. Also explosive detection techniques appropriate for use against surface IEDs may be inappropriate for the detection of buried explosives and explosive ordnance.

2. Technology Approaches

a. Ion Mobility Spectrometry (IMS)

IMS is a promising technique for detecting buried explosives. An ion mobility spectrometer is composed of a sample inlet, an atmospheric pressure ion source, an ion-molecule reactor, an ion-drift spectrometer, and a detector. Ions formed in the reactor are injected into the drift region by an applied electric field. The ions are separated by their mobility as the ions travel through a drift gas. By plotting the ion current as a function of time, the ion mobility is established because the heavy ions move at slower speeds. The relative intensities of ion peaks are influenced by concentration and by the stability and

Table II-3. Chemical Vapor/Solid Particulate Explosive Technologies Detection Capabilities

| Technology | Explosive | | |
|--|-----------|-----------------|---------|
| | TNB | TNT | DNT |
| Ion mobility spectroscopy (IMS) | x | 10 ppt | x |
| Photoacoustic spectroscopy (PAS) | < 1 ppb | < 1 ppb | < 1 ppb |
| Resonantly enhanced multiphoton ionization (REMPI) | – | 100 ppt | – |
| Cavity ring-down spectroscopy (CRDS) | 100 ppt | – | – |
| Laser induced breakdown spectroscopy (LIBS) | – | 100 ppb | – |
| Optical sensor array (OSA) | 80 ppb | | 20 ppb |
| Surface acoustic wave (SAW) | | 100 ppt | |
| Thermo-redox (TR) detectors | < 1 ppb | < 1 ppb | < 1 ppb |
| Chemical luminescence | x | x | x |
| Gas chromatography (GC) | < 1 ppb | < 1 ppb | < 1 ppb |
| Biological systems: Canines | – | ~ 500–1,000 ppt | – |
| Reversal electron attachment detectors | – | x | – |
| Polymer fluorescence | – | 6 ppt | – |

Note for Table II-3: An “x” in the matrix indicates that explosive detection has been reported but that no technology sensitivities were reported.

composition of the explosive sample. Hand-portable gas chromatography and IMS have been combined (GC/IMS) for portable explosive detection.

b. Infrared (IR) Spectroscopy

IR spectroscopy uses IR radiation to excite vibrational transitions in explosives. In the near IR, harmonics and combination transitions can be observed. In the mid IR, transitions associated with fundamental molecular vibrations can be measured. In the far IR, rotational transitions are observed in the gas phases of an explosive. IR detectors require a sampling section, a section to catalytically decompose the explosives into stable molecular fragments, and a section that uses a tunable laser to desorb the explosive fragments. Detection limits in the parts per trillion (ppt)⁷ range have been achieved.

⁷ One part in 10¹².

c. Bioluminescence

Bioluminescence occurs when light is emitted or derived from a chemical reaction occurring in a living system. Even with low-light emission levels, systems have been built that can detect ppt ranges over a 20-minute interval.

d. Photoacoustic Spectroscopy (PAS)

The optoacoustic effect was observed by Alexander Graham Bell (1847–1922) over a century ago.⁸ PAS uses a pulsed source of radiation, a photodetector, a cell to confine the gas of interest, a transducer to convert pressure into electrical signals, and an instrument to measure the transducer output. The excitation energy is tuned to a wavelength known to be absorbed by the explosive of interest. Modulation of the incident light produces a temperature rise, which, in turn, is detected as a pressure wave within the cell containing the sample gas.

e. Resonantly Enhanced Multiphoton Ionization (REMPI)

REMPI is a technique that uses a supersonic nozzle inlet, a tunable laser, and a time-of-flight (TOF) mass spectrometer. The nozzle inlet cools the gas molecules to approximately 20 K, which simplifies the laser absorption spectrum. (At higher temperatures, many more higher energy states exist for every element/compound present. Each higher energy state for each compound has its own spectral line.) The laser is tuned to a resonance transition. The ionized gas molecules are then measured in a mass spectrometer.

f. Electron Capture Detection (ECD)

ECD uses radioactive Nickel-63 to ionize a gas sample. This forms a stable cloud of free electrons in an ECD cell. When electronegative compounds enter the cell, these compounds combine with some of the free electrons. The gas in the chamber is characterized by the standing current of electrons going to an anode. Nitrogen dioxide (NO₂)

⁸ Optoacoustic imaging is an imaging technology based on the photothermal effect—a phenomenon associated with electromagnetic radiation; produced by the photoexcitation of material, resulting in the production of thermal energy (heat)—and can be used to obtain images of structures in turbid environments. The optoacoustic technique combines the accuracy of spectroscopy with the depth resolution of ultrasound. The oldest technical application of the photothermal effect is believed to be the photophone, a communication device invented by Alexander Graham Bell in 1880. Bell observed the emanation of audible sounds from a transparent tube containing material in suspension when a modulated light source is focused on the tube. Modulation of the light impinging on an absorbing substance will produce a similar modulation in temperature via the photothermal effect.

molecules with high electron affinities lower the standing current. The reduction in current identifies the presence of explosive ions.

g. Cavity Ring-Down Spectroscopy (CRDS)

CRDS features an optical resonator that uses high-reflectivity mirrors to perform vapor concentration measurements. Light is circulated in the cavity, and its decay rate is measured by monitoring light transmitted through the mirrors. The decay rate depends on the dimensions of the cavity, the reflectivity of the mirrors, and the concentration and absorbance cross section of the vapor sample. CRDS can detect sub-ppb concentrations of TNT.

h. Laser Induced Breakdown Spectroscopy (LIBS)

LIBS uses a nanosecond laser pulse to breakdown a sample. The emission spectra of the resulting laser plume are analyzed. The spectra contain emissions from ionic, atomic, and molecular species that were produced from the breakdown. Explosive detection and identification can be obtained by comparing the spectrum to a library of experimentally obtained spectra or by examining the intensity ratio of the nitrogen and oxygen peaks.

i. Optical Sensor Array (OSA)

An OSA contains a large number of microsensor beads (with micrometer diameters) placed in small wells on the end of a fiber-optic cable. Nitroaromatic compound (NAC)-specific microsensors are polymer-based beads with electron-donating groups that attract electron-accepting nitroaromatic compounds. The time-dependent fluorescent response of these sensors to vapor pulses depends on the vapor compositions and exhibits particular shapes for different analytes. A charge-coupled device (CCD) camera monitors the fluorescent response of the sensors in the array and compares the resulting pattern to patterns previously established to be associated with specific NACs.

j. Surface Acoustic Wave (SAW)

SAW technology use the piezoelectric effect to selectively attract and absorb explosive molecules. A transmitter sends acoustic surface waves that are detected by a receiver. The mass of adsorbed molecules changes the frequency of the waves. The change in frequency is used to identify explosive molecules.

k. Terahertz Spectroscopy

Terahertz spectroscopy is used to identify the presence of explosives through their reflected or transmitted spectrum. Sources of terahertz radiation currently require femto-second pulse lasers and nonlinear optical elements. For trace-gas detection, the transmission spectrum is used. For bulk detection, soil can strongly attenuate terahertz signals.

l. Thermo-Redox (TR) Detectors

Thermo-Redox (TR) technology is based on the thermal decomposition of explosive molecules and the subsequent reduction of NO₂ groups present in those compounds. NO₂ molecules are detected with an electrochemical detector. TR detects only the NO₂ molecules and cannot distinguish between explosives and nonexplosives that contain those molecules. It does not detect explosives that do not contain NO₂ groups.

m. Chemical Luminescence

Chemical luminescence, or chemiluminescence, is based on the detection of IR light emitted by electronically stimulated NO₂ molecules. The amount of light emitted is collected by a photomultiplier tube with a red filter and is proportional to the amount of NO₂ and nitrate (NO₃) inside the reaction chamber.

n. Gas Chromatography (GC)

GC measures gas flows over special beads designed to interact more strongly with one chemical substance than with chemical substances. Gas chromatographs are also paired with other vapor detectors to increase detection performance by adding selectivity (i.e., identifying molecules).

o. Biological Systems: Immunochemical Sensors

Immunochemical sensors use antibodies designed to bind with specific molecules. Once the antibody binds to the appropriate molecule, the properties of the antibody are changed so that it can be measured by optical transmittance or by fluorescence.

p. Biological Systems: Animals

Biological systems (bees, canines, rats) are trained to detect specific explosive compound(s). The technique requires special human handlers to ensure proper maintenance and performance of the animals.

q. Biological Systems: Plants

Using a transgenic plant bioindicator implanted in the annual weed Thale Cress (*Arabidopsis thaliana*) that detects NO₂ from buried land mines by changing color from green to red.

r. Reversal Electron Attachment Detectors

Reversal electron attachment detectors capitalize on the fact that compounds with highly electronegative groups (NO₂ in explosives) have a high affinity for electrons. Low-energy electrons (less than 10 MeV) efficiently attach to NO₂ compounds and either form a characteristic anion (atom or group of atoms carrying a negative charge) or initiate a unique dissociation pattern. Electrons with very low energies are produced by firing electrons into an electrostatic mirror, which brakes the electrons to near-zero kinetic energies.

s. Electronic Noses

Electronic noses (e.g., FIDO)⁹ are being developed for the detection and classification of odors, vapors, and gases. An electronic nose consists of a chemical sensing system or sensor array that is tied to a pattern recognition system. The sensing system can be an array of several different sensing elements in which each sensor element measures a different property of the sample. Alternatively, the sensing system can be a single sensing device, such as a spectrometer that provides a multitude of measurements for each chemical or chemical compound. A database of labeled signatures is used to train a pattern recognition system.

⁹ FIDO was developed by a team of electronic, computer, and chemistry experts to do what a dog's nose does. The 3 lb, battery-powered device detects explosives by the unique scent the explosives give off. Explosives are chemical compositions that are constantly breaking down and shedding distinctive collections of molecules. Dogs can detect them and so can FIDO. However, dogs are usually trained to detect only one type of explosives (usually TNT), and have their bad days. FIDO can detect several types of explosives, can match a trained dog in its capability to detect explosives, and is more reliable and tireless than a dog. (Source: <http://www.strategypage.com/htmw/htinf/articles/20060628.aspx>).

t. Polymer Fluorescence

Polymer fluorescence uses a polymer that greatly increases the sensitivity of chemical detection systems for nitroaromatic explosives. The polymer undergoes a lasing action at lower operating powers than those of previous polymers. The stimulated light emission from the lasing modes of the polymer displays high sensitivities to explosive vapors. When exposed to ultraviolet (UV) light above a certain threshold, the semiconducting organic polymer material begins the lasing process. When TNT is present, the TNT binds to the semiconducting organic polymer surface and quenches the beam. A polymer has also been identified for RDX detection.

u. Preconcentrators

Preconcentrators are not a detection technology per se. They increase the amount of target material reaching a detector by filtering air and collecting target material to be sent directly to the detector. Preconcentrators are used with many other forms of vapor detection devices to increase the sensitivity of these devices.

III. BULK DETECTION

A. BACKGROUND

Buried detection of bulk explosives requires soil-penetrating and explosive-casing penetration methods such as electromagnetic radiation, low-energy microwaves, x-rays, gamma rays, and neutrons. After stimulating responses from the bulk explosives, the subsequent radiation must then also travel through the casing and the soil before it can be detected. Only one-sided access is available for the detection of buried items.

Military explosives contain oxygen, nitrogen, carbon, hydrogen, and other organic compounds. Explosives are rich in oxygen and nitrogen but poor in carbon and hydrogen. Bulk explosive detection techniques seek to detect the high concentration of oxygen and nitrogen or to exploit the element concentrations of these gases to suggest the presence of buried explosive devices.

As with all detection technologies, the major problem with detecting buried bulk explosives is the large variety and amounts of clutter. Radiation techniques can cause numerous reactions with the clutter and with soil impurities. If the radiation techniques are used as scanning sensors, the ultimate result is that metric tons of soil must be interrogated to find suspected items. The approaches described in this section are generally limited to applications in which the probing radiation technology is used only after suspected sites have been identified by “anomaly” detectors [e.g., metal detectors and ground-penetrating radars (GPRs)]. Even with these restrictions, however, the size of the bulk explosive and its burial depth play a major role in the potential effectiveness of the detection technologies discussed herein.

B. RADIATION DETECTION OF EXPLOSIVES

Two types of radiation are used to probe for the detection of buried explosives: electromagnetic radiation and neutron radiation. Appendix C contains data sheets for most of the different forms of radiation technologies described here.

1. Electromagnetic Radiation Detection of Explosives

a. X-rays

Lateral Migration Radiography (LMR)

LMR is a new imaging approach that uses both single-scattered photons and the lateral transport of multiple-scattered photons to form separate images. The separate sensing of the first-scatter photons permits removal of the surface component in the final image. The advantage of this approach includes the fact that it can be used in a scanning mode and probably will have a low false alarm rate. The technique however is specific for explosives, since the large angle scattering is related to the z factor of the explosives. Other buried objects with the same z factor will also be imaged. The technique will only scan to a depth of approximately 4 in., which is compatible with tactical mine detection but not with buried ordnance detection.

Photoelectric Effect and Pair Production

Compton scattering with explosives occurs at energies above 20 keV. Other techniques that use the photoelectric effect (100–150 keV) and pair production (energies above 1.02 MeV) require large sources and require significant radiation shielding. These higher energy approaches are used to generate images to suggest the presence of explosives.

b. Electron Spin Resonance (ESR)

ESR is based on the magnetic moment associated with the intrinsic spin of electrons or free radicals. Its use is limited to the few materials that have free spins. Most organic compounds are processed in ways that preclude free radicals. Black powder, not generally used in mines and current ordnance, is sensitive to ESR.

c. Nuclear Magnetic Resonance (NMR)

NMR can be used to identify atomic configurations in molecules. The characteristic absorption of energy of certain spinning nuclei (e.g., ^1H , ^{13}C) in strong uniform magnetic fields can be stimulated by adding a second, weaker radio-frequency (RF) field perpendicular to the magnetic field. Absorption is registered when these nuclei undergo transitions from one alignment in the applied field to an opposite alignment. Because the

detection of buried explosives provides only one-sided access, NMR is not well suited to producing strong, uniform magnetic fields beneath the earth's surface.

d. Nuclear Quadrupole Resonance (NQR)

NQR is a technique in which an induced spin resonance is used to identify the presence of explosive compounds. NQR frequencies depend on the product of the ^{14}N nuclear quadrupole moment and the electric field gradient particular to the compound solid in which the nucleus is embedded. The electric field gradient depends on the electronic bonding to the nitrogen. In NMR, the splitting of the energy states is caused by a large external magnetic field. In NQR, the splitting of the energy states is caused by the interaction of the nuclear quadrupole moment and the molecular-induced electric field gradient. NQR does not share the requirement for a strong external magnetic field because NQR will only work with nuclei that possess their own intrinsic magnetic moment. Because NQR, like NMR, uses an applied external RF field to induce resonance, it cannot be used to detect explosives in metal mines or ordnance casings. It is limited to detection of explosives in plastic- and wood-cased mines and ordnance.

The Office of Naval Research (ONR) has recently completed an NQR program that incorporates NQR detection with the U. S. Army's AN/PSS-14¹⁰ hand-held mine detector. The specificity of the NQR technique provides an ability to achieve remarkably low false alarm rates during mine detection. In field tests at Yuma Proving Ground (YPG) in Arizona (December 2005) and in subsequent field tests held at Aberdeen Proving Ground (APG) in Maryland (June 2006) and at Fort A. P. Hill in Virginia (June 2006), the combined detector demonstrated an ability to clear false alarms and to maintain a high probability of detection for antipersonnel (AP) and AT mines buried at tactical depths. In the tests at APG, NQR demonstrated the capability to reduce the number of false alarms by a factor of 20. During the less cluttered tests at YPG, NQR demonstrated an ability to reduce the number of false alarms by a factor of 8. In the tests at Fort A. P. Hill, a lightweight (less than 3 lb) search head, together with a supporting backpack (less than 30 lb), was demonstrated. The entire system was powered with military batteries.

¹⁰ The new Advanced Mine Detector (AMD) incorporates NQR technology to provide the next step in mine detection by using sensors that can detect chemically unique explosive signatures from buried plastic case anti-tank (AT) and AP mines. The AMD combines NQR with the new AN/PSS-14 mine detector to maintain a high probability of detection with significantly lower false alarms.
Source: http://www.onr.navy.mil/media/releases/image_gallery/default.asp?categoryID=5

NQR detection does have limitations. The high Q antenna used to sense the resonance signals is limited to tactical burial depths (AP mines: 1 in. of soil overburden, AT mines: 3 in. of soil overburden). Major advancements in NQR technology are needed to improve its performance, particularly the ability to detect more deeply buried mines and ordnance. NQR performance decreases in high radio frequency interference (RFI) environments.

The present NQR system is not a scanning system, principally because the spin-lattice relaxation time of TNT (3 sec) precludes that mode of detection. The tested system used the electromagnetic induction (EMI) and GPR sensors to identify suspected mine sites. The NQR coil was then placed atop the spot and an NQR pulse sequence was initiated to search for RDX, tetryl, and TNT. The total time to clear a clutter site was approximately 5 min. Targets containing RDX or tetryl were quickly identified (less than 1 min), and TNT mines were identified in the 2- to 5-min time frame.

e. Raman Spectroscopy

Raman scattering is initiated when a laser illuminates explosive molecules. Photons emitted during this process are used to identify the target compound. When photons strike a molecule in its ground state, the molecule can be raised into a higher vibrational state. If the molecule returns to its ground vibrational state and emits a photon, it is considered Rayleigh scattering. If excited molecules do not return to the ground state but fall to some other excited vibrational state, the molecule will emit a photon of lower energy than the exciting photon. This is called Stokes-type Raman scattering. If a photon is absorbed by a molecule that is in the first excited state, the molecule is raised to a high nonstable energy state. If the molecule then returns to the ground state, it emits a photon of higher energy than the original incident photon. This is defined as anti-Stokes-type Raman scattering. The probability of a molecule undergoing an anti-Stokes transition is lower than the probability of it undergoing a Stokes-type transition. The intensity of Stokes lines is, therefore, higher than that for anti-Stokes Raman scattering. The requirement for the appearance of the Raman effect is that the polarizability of molecule is changed by the incident radiation

Optical access is required for this process. The discovery of buried explosives has to be accomplished through the detection of explosive vapor or through scattering by microscopic particles' explosive residue. The literature gives the Raman bands for

different explosives. As with all trace-gas and trace-solid detection approaches, this technique is sensitive to the amounts and types of trace elements.

2. Neutron Radiation Detection of Explosives

Active neutron techniques provide highly penetrating probes that generate specific and detectable reaction products. The soil, mine or ordnance casing, and the penetrated explosive react in different ways to an incident beam of neutrons. The interactions result in specific detectable radiation. The energy, intensity, and spatial distributions of the interaction of neutrons result in detected radiation with respect to the incident beam of neutrons.

a. Thermal Neutron Analysis (TNA)

TNA characterizes explosives by their nitrogen and hydrogen content. A thermal neutron (~ 0.025 eV) interacts with a nitrogen-14 nucleus to produce a 10.85 MeV gamma ray. The emission of the gamma indicates the presence of nitrogen. Taken together with a hydrogen signature (2.223 MeV gamma), the presence of a bulk explosive is suggested. The dependability of this approach depends on achieving a high signal-to-noise ratio (SNR). The presence of other compounds of nitrogen, such as fertilizer, cause false alarms.

Both natural sources and neutron generators can be used for mine and UXO detection. A vehicle-borne detector approach was tested against AT mines by the Belvoir Research and Development (R&D) Center (Ft. Belvoir in Virginia) in the 1990s in both a scanning and a confirmation sensor mode. The number of false alarms incurred prevented its further development.

b. Fast Neutron Analysis (FNA)

TNA is not applicable to the detection of oxygen or carbon. Oxygen and carbon can be detected by characteristic gamma rays emitted because of fast neutron inelastic collisions. FNA uses neutron energies, roughly 5–7 MeV. Carbon, oxygen, and nitrogen produce relatively intense gamma rays because of the (n,n'gamma) reaction. The characteristic gamma rays occur at 4.43 MeV for carbon, at 6.13 MeV and 3.84 MeV for oxygen, and at 1.63 MeV, 2.3 MeV, and 5.1 MeV for nitrogen.

c. Pulsed Fast-Neutron Analysis (PFNA)

PFNA combines gamma ray spectroscopy with neutron TOF. It measures the result of the interaction of fast neutrons and explosives. In addition, it provides timing information using coincidence and anticoincidence measurements to provide background reduction and 3-D spatial resolution. Monoenergetic neutron beams, combined with fast electronics, are needed for optimum results. The presence of hydrogen cannot be determined using pure FNA.

d. Gamma-Neutron Reaction Technology

At 10 MeV (gamma), nitrogen undergoes a reaction $^{14}\text{N}(\text{n},\gamma)^{13}\text{N}$. This reaction peaks at 16 MeV and falls to a minimum at 2.5 MeV. ^{13}N is a positron emitter with a half-life of 10 min. It produces no gamma rays. The emitted positrons annihilate electrons, which, in turn, emit two spatially opposed gamma rays at 511 keV for each electron. Detection of the 511-keV gammas indicates the presence of nitrogen. A variant of this approach was funded by the Defense Advanced Research Projects Agency (DARPA) and evaluated by the Belvoir R&D Center in the 1990s. However, false alarms were a problem, and the program was terminated.

e. Minebuster Technology

Neutrons are produced in a self-colliding plasma through the deuteron plus Boron (d+B) reaction. Fast neutrons (6–8 MeV) react with nitrogen and other elements. The $^{14}\text{N}(\text{n},\text{n}'\gamma)^{14}\text{N}$ reaction produces a 4.1-MeV gamma ray. Neutrons also react with the soil and casing material. At 4.1 MeV, a quasi-triple coincidence is needed for a “true” event to be registered. The coincidence technique can provide background reduction of six orders of magnitude or more. Carbon, which is present in most soils, also produces approximately 4.1-MeV gamma rays. A “double differential” analyses technique is used. The neutron energy is varied, and the derivative of the 4.1 gamma intensity is calculated. A peak in the derivative spectrum occurs if nitrogen is present. The U.S. Army Night Vision and Electronic Sensors Directorate (NVESD) funded a Small Business Innovation Research (SBIR) program to evaluate this technology in 2000. Some promising results were obtained for tactically buried AT mines.

IV. IMPROVISED EXPLOSIVE DEVICES (IEDs)

A. BACKGROUND

IEDs, or remotely controlled mines, are the major source of U. S. casualties in Iraq. The use of command-detonated mines dates to the U.S. Civil War when Confederate forces used black powder and buried artillery shells to attack advancing Union units. Major General William Tecumseh Sherman countered these tactics by forcing captured Confederate prisoners of war to march in front of Union forces. Remotely controlled mines and booby traps were also a major cause of U. S. casualties in Viet Nam.

IEDs and mines are weapons of choice used in asymmetric warfare¹¹ by the smaller force. The interest in developing countermeasures to mines and IEDs waned after the Viet Nam War, and relatively small resources were devoted to IED/mine R&D. As a result, for the similar threat that the United States faces today, only scattered and limited-effectiveness countermeasures can be immediately applied to the problem.

B. CHEMICAL TRACE DETECTION OF IEDs

The two roles in which chemical trace detection can be applied to the detection of deployed IEDs are (1) *standoff detection* in which the sensor can detect surface explosives at a safe distance (greater than 50 m) and (2) *remote detection* in which chemical sensors are transported to the suspected IED on a robot or remotely controlled platform. Chemical trace detection sensors can also be deployed at checkpoints to determine if vehicles or people are transporting explosives or explosive devices. In all these cases, one must assume that an explosive vapor or solid is available for detection. If IEDs are buried, camouflaged, or otherwise hidden from direct view, the following approaches will be useful only after the IED has been located and exposed.

¹¹ Asymmetric warfare describes a military situation in which two belligerents of unequal power or capacity of action interact and take advantage of the strengths and weaknesses of themselves and their enemies. This interaction often involves strategies and tactics outside the bounds of conventional warfare.

Not surprising, chemical trace detection can only play niche roles in solving the IED problem. However, chemical trace detection can play important roles as a “complementary sensor” that provides specific information in certain conditions or scenarios.

The National Research Council (NRC) of the National Academy of Sciences (NAS), in its report on standoff explosives detection techniques (Ref. 16), states that “to design an effective standoff explosives detection system—explosives detection where physical separation puts individuals and valuable assets outside the zone of severe damage from the potential detonation of an explosive device—the following issues must be considered: Multiple sensors of different types increase the number of possible indications that can be searched for in the environment. Both specificity and sensitivity can continue to increase with additional sensor types, as long as there are indications that each sensor type can find an explosive if an explosive is present during its interaction with the environment. The result coming from a standoff explosives detection system is not static, nor is it desirable that it be static. Novel threats will be recognized only incidentally via intersection with threat parameters currently considered by the system” (Executive Summary, p. 4).

1. Chemical Standoff Detection of Explosives

Currently, no commercial systems that can reliably and robustly detect explosives on the surface of IEDs at safe standoff distances are available. Four technological approaches have the potential to detect explosives at standoff distances: LIBS, terahertz spectroscopy, bioluminescence, and Raman spectroscopy. All these approaches are currently in R&D, and, at this time, no unique “fingerprint” in the spectroscopic spectrum has been identified that is unique to individual explosives. In addition, two of the techniques (terahertz spectroscopy and bioluminescence) have other problems that could limit their robustness for standoff detection. Terahertz electromagnetic waves can be absorbed in different atmospheric conditions. Bioluminescence would require that specific biological material be spread over suspected areas many hours before the luminescence could be reliably observed.

2. Remote Chemical Detection of Explosives

Because remote detection suggests that the chemical sensor is being transported to a suspected IED by a remotely controlled platform or robot, virtually any of the chemical trace detection technologies would be a candidate for remote explosive detection. The

most mature commercially available technologies are generally systems that incorporate preconcentrators, an ion mass spectrometer, and/or a gas chromatograph. These types of sensors have been incorporated and used in EOD robots. Again, the success of such systems relies on the IED having detectable amounts of explosive vapor or solid on the external surface.

3. Trace Detection of Explosives at Checkpoints and Portals

All the technologies discussed in Section II are also potentially useful in detecting explosives on people and vehicles at checkpoints and portals. The present commercial systems use some combination of preconcentration, ion mass spectrometers, and/or gas chromatographs. The success of detecting explosives at checkpoints and portals is entirely dependent on the external presence of the explosive on people and equipment. Amplified fluorescence polymers (Fido)¹² are being used in Iraq.

C. BULK DETECTION OF IEDs

Radars and IR sensors can be used at standoff distances to detect IEDs, but they are traditionally used as an anomaly detector. They can be used as scanning sensors to detect buried and surface IEDs. Traditionally, radars, IR, and EMI techniques have been used in hand-held and vehicle-mounted mine detectors. However, these techniques are used to detect bulk anomalies and are not used as explosive-specific detectors. Terahertz techniques potentially could also be used in a bulk anomaly detection mode as better sources are developed.

1. Standoff Portal Bulk Detection of Explosives

X-ray and neutron radiation techniques could be developed for “standoff” portal detection of IEDs, in which vehicles or objects would be passed through a checkpoint or portal and screened for explosives. Radiation techniques are not suited for use as standoff vehicle-mounted detectors because radiation systems are relatively large, may require radiation shielding, and are not suitable scanning detectors.

¹² Fido, an electronic nose, can locate land mines by sensing their chemical vapors. Modern plastic-encased mines are undetectable to World-War-II-era metal detectors.

2. Vehicle-borne Improvised Explosive Device (VBIED) Portal Bulk Detection of Explosives

VBIEDs can be detected using specially constructed x-ray or neutron radiation portal detectors. The large amounts of explosive typically carried by VBIEDs would provide more than ample signal for most x-ray and neutron radiation explosive detection techniques. Such portal detection would be confined to secure areas because the size and stationary nature of explosive interrogation would mean prolonged exposure to counter-insurgents and their weapons.

D. SUMMARY

Explosive-specific detection will not provide vehicle-mounted detection at normal vehicle operating speeds. Many forms of explosive-specific detection are commercially available and have been used to detect individuals, vehicles, and containers transporting explosives and explosive devices. Some of the commercially available explosive-specific detection capabilities have been used to combat the IED problem. However, explosive-specific detection technologies require direct explosive exposure and require finite lengths of time for detection and identification.

V. AVAILABILITY AND APPLICABILITY OF EXPLOSIVE DETECTION SYSTEMS

A. BACKGROUND

For explosive detection systems to be useful in Unexploded Ordnance Center of Excellence (UXOCOE) applications, two issues are paramount: hardware and supporting systems (training, logistics, and so forth) must be available, and the explosive detection systems must meet the needs of any prospective user.

The following sections list the availability/applicability of selected technologies and the specific niche roles they could play in UXOCOE scenarios. The last section also show the emerging technologies that could be applicable to the UXOCOE missions in the mid to far time frame.

B. AVAILABILITY OF CHEMICAL TRACE DETECTION TECHNOLOGIES

Table V-1 lists trace-gas detection technologies, the ability of some technologies to be used in a standoff detection mode, and an indication of the maturity of each type of system. It must be noted that the commercial off-the-shelf (COTS) designation is limited to hardware that is applicable to the detection of buried explosives. Some of the trace detection technologies in Table V-1 may have COTS systems available but are only useful inspecting baggage or travelers at airports.

C. AVAILABILITY OF BULK DETECTION TECHNOLOGIES

Table V-2 lists availability of bulk detection technologies. The items are listed as commercially available only if the systems are applicable to detecting buried UXO.

D. APPLICABILITY OF EXPLOSIVE DETECTION TECHNOLOGIES TO UXOCOE REQUIREMENTS

Table V-3 shows a mission area comparison of mission requirements across the UXOCOE spectrum. Comparing and contrasting the UXOCOE mission requirements, it

Table V-1. Availability of Chemical Trace Detection Technologies

| Technology | Standoff Capability | Maturity |
|---|---------------------|-----------------|
| Ion mass spectroscopy (IMS) | No | COTS |
| Bioluminescence | Yes | S&T Development |
| Electron capture detection (ECD) | | S&T Development |
| Cavity ring-down spectroscopy (CRDS) | | S&T Development |
| Laser induced breakdown spectroscopy (LIBS) | Yes | S&T Development |
| Optical sensor array (OSA) | | S&T Development |
| Terahertz spectroscopy | Yes | S&T Development |
| Thermo-redox (TR) detectors | | S&T Development |
| Chemical luminescence | Yes | COTS |
| Gas chromatography (GC) | | COTS |
| Biological systems | Yes | COTS |
| Reversal electron attachment | Yes | S&T Development |
| Electronic noses | | S&T Development |
| Polymer fluorescence | | COTS |
| Preconcentrators | | COTS |

Table V-2. Availability of Bulk Detection Technologies

| Technology | Standoff | Maturity |
|--|----------|-----------------|
| <i>Electromagnetic Radiation</i> | | |
| Lateral migration radiography (LMR) | | Prototype |
| Photoelectric effect and pair production | | S&T Development |
| Electron spin resonance (ESR) | | S&T Development |
| Nuclear magnetic resonance (NMR) | | S&T Development |
| Nuclear quadrupole resonance (NQR) | | Prototype |
| Raman spectroscopy | Yes | S&T Development |
| <i>Neutron Radiation</i> | | |
| Thermal neutron analysis (TNA) | | Prototype |
| Fast neutron analysis (FNA) | | S&T Development |
| Pulsed fast-neutron analysis (PFNA) | | COTS |
| Gamma-neutron reaction technology | | S&T Development |
| Minebuster technology | | Prototype |

Table V-3. Comparison of UXOCOE Mission Area Requirements

| Mission Requirement | Mission Areas | | | | |
|---------------------|--|------------------------------|-----------------------|--------------------|-------------------|
| | Countermine | EOD | Humanitarian Demining | Munitions Response | Range Sustainment |
| Effectiveness | < 100% | ~ 100% | ~ 100% | ~ 100% | ~ 100% |
| Speed of detection | Critical | Critical | Noncritical | Noncritical | Noncritical |
| Ease of use | Complex | Complex | Simple | Complex | Complex |
| Size/weight | Critical | Critical (mission dependent) | Noncritical | Noncritical | Noncritical |
| Maturity | High (rugged) | High (rugged) | COTS | COTS | COTS |
| Cause of casualties | Mine/UXO Direct fire Indirect fire | UXO | UXO | UXO | UXO |

shows that countermine can tolerate less than 100 percent detection of mines (movement under direct and indirect fire), while the other mission areas require approximately 100 percent detection. Speed of detection is a critical requirement for countermine and EOD but is not critical for humanitarian demining, munitions response, and range sustainment. Complex systems and training can be tolerated in all UXOCOE mission areas with the exception of humanitarian demining (because of the high reliance on local populace to clear mines and minefields). Size, weight, and ruggedness are critical requirements for countermine and EOD but are not critical for the other UXOCOE mission areas. Lastly, in assessing the probability of casualties, countermine is the only mission area that must deal with direct and indirect fire during many different type of countermine operations.

E. NICHE ROLES FOR EXPLOSIVE DETECTION

Using the information from Table V-1 and Tables V-2 and V-3, we concluded that the some of the current technologies could be used in niche roles (see Table V-4). All the items in Table V-4 could be obtained in limited amounts for specific tests.

The principal issue is that a consistent demand does not exist for these types of items in the marketplace. The LMR backscatter approach has also been used successfully to evaluate foam for the National Aeronautics and Space Administration (NASA) shuttles. Canines not only have to be trained, but their training also has to be kept current.

Table V-4. Niche Roles for Current Prototype and COTS Items

| Technology | Role |
|---|---|
| Ion mass spectrometry (IMS) Chemical luminescence Gas chromatography (GC) Polymer fluorescence Preconcentrators | Scan people and items at checkpoints |
| Canines | Rapidly sniff and detect buried and surface mines and UXO |
| Lateral migration radiography (LMR) | Identify AT and AP mines |
| Nuclear quadrupole resonance (NQR) | Identify plastic AT and AP mines |
| Pulsed fast-neutron analysis (PFNA) | Identify explosive-filled UXO |

Many of the trace chemical detection techniques are used in airports and security checkpoints to evaluate passengers and the baggage. The same systems have limited utility in detecting buried explosives.

F. NICHE ROLES FOR EXPLOSIVE DETECTION TECHNOLOGIES AVAILABLE IN THE NEAR TIME FRAME (5 YEARS)

Table V-5 shows chemical trace detection technologies that soon may be available commercially. Bioluminescence could provide standoff detection but would require spreading biological material over suspected areas hours or days before optimal signals could be obtained.

Table V-5. Niche Roles Available in the Near Time Frame for Selected Chemical Trace Detection Technologies

| Technology | Role |
|--|---|
| Optical sensor array (OSA) Thermo-redox (TR) detectors | Portal detection |
| Biological Systems: Immunochemical sensors Bioluminescence Chemical luminescence | Use in standoff detection of areas containing UXO and mines |

G. R&D ITEMS

Table V-6 shows emerging technologies that could be applicable to the UXOCOE missions in the mid to far time frame (5 to 10 years).

Table V-6. Emerging R&D Techniques for Detecting Explosives

| Technology |
|---|
| Photoacoustic spectroscopy (PAS) |
| Cavity ring-down spectroscopy (CRDS) |
| Laser induced breakdown spectroscopy (LIBS) |
| Terahertz spectroscopy |
| Reversal electron attachment |
| Polymer fluorescence |
| Gamma-neutron reaction technology |

LIBS is also called laser induced plasma spectroscopy (LIPS). Both LIBS and terahertz spectroscopy can be used at standoff distances but require a direct line of sight (DLOS) to the explosive. DLOS would only be applicable to the minute amounts of trace explosives or ERCs on the soil surface.

VI. CONCLUSIONS

Detection of buried explosives can be accomplished through trace chemical detection of explosive vapors or trace detection of explosives and ERCs condensed in the top soil above the buried UXO. Electromagnetic and neutron radiation techniques can also be used to detect bulk explosives buried beneath the earth's surface. The technical approaches available have been described in this report and its appendixes. Explosive detection techniques generally require acquisition times on the order of seconds to minutes. The sole exception to this is x-ray backscatter LMR technique, which is not in itself an "explosive-specific" detection technique. The fact that sensor acquisition times are on the order of seconds to minutes precludes the use of explosive detectors as scanning sensors or primary sensors. The best role for explosive detectors is to be used only after scanning sensors have identified likely targets.

The transport codes and the measured data clearly show that trace chemical detection is not a robust technology for the detection of buried explosives. Metal-encased UXO that are not broken or contain little or no trace explosives on their exterior do not provide a true target. Further, the transport code shows the movement of the ERCs, with the concomitant result that even valid detection of explosives on the soil surface does not mean that the buried explosive is directly below the point of detection. Explosive vapors can give a more realistic estimate of the placement of buried explosives, but the reliable field measurements we found to date are limited to the detection of TNT and some of its related products.

Using the current technologies to detect bulk explosives appears limited to the top 20 cm of the earth's surface. While large and small mines can be found with x-ray backscatter LMR technology, NQR, and PFNA, none of the techniques are capable of reliably finding deeply buried UXO.

Explosive detectors can play a "niche" role in finding buried mines and UXO. Section V addresses these roles. Once anomalies have been identified, explosive detection techniques can be a valuable tool in determining the presence of explosive(s). In scenarios where time permits, the addition of this type of detection, substantially lower false alarm rates can be achieved.

All explosive detection technologies are applicable to checkpoint security and for the incorporation on robots for remote sensing. Standoff detection (greater than 50 m) of surface explosives can be achieved by emerging technologies, such as LIBS, terahertz spectroscopy, bioluminescence and Raman spectroscopy.

The vast amount of surveyed literature pointed to the fact that only a few field measurements appeared to have been acquired with requisite equipment that was able to identify clearly the background levels and the actual amounts and types of explosive compounds and explosive sources. JUXOCO needs to facilitate workshops that address the acceptable equipment and standardize the data collection and documentation and the procedures for future use of chemical trace explosive detectors.

The development of an open-source, nonproprietary code would aid in the understanding of measurements at different test sites and under different environmental conditions. To complement the development of this open-source code, workshops could be conducted to standardize data collection procedures to define:

- Soil properties
- Water convection in soil
- Diffusion in explosives in soil
- Relative amounts of ERCs
- Sorption to soil and vaporization into the air layer
- Bulk explosive in region of tests
- Transfer of explosives between phases (i.e., gas or solid).

VII. RECOMMENDATIONS

A limited database exists in which chemical trace detection is reported with meaningful equipment to document background levels, actual amounts and type of explosive effluents or soil explosive composition, and reliable field sources to calibrate their instruments. It is recommended that the UXOCOE play a leadership role to establish standards for field measurements in trace detection technologies through workshops to

- Define protocols of measurements and techniques
- Specify measurement instruments
 - Backgrounds
 - Point-of-measurement samples
- Specify appropriate sources for calibration of instrumentation.
- Encourage field measurement at different test sites to support future open-source code development through measurements of
 - Soil properties
 - Water convection in soil
 - Diffusion in explosives in soil
 - Relative amounts of ERCs
 - Sorption to soil and vaporization into the air layer
 - Bulk explosive in region of tests
 - Transfer of explosives between phases (i.e., gas or solid).

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GLOSSARY

| | |
|------------|---|
| 1-D | one-dimensional |
| 2,4-DNT | 2,4-Dinitrotoluene |
| 2-D | two-dimensional |
| 3-D | three-dimensional |
| AAAS | American Association for the Advancement of Science |
| AFB | Air Force Base |
| AFP | amplifying fluorescent polymers |
| AMD | Advanced Mine Detector |
| AN | Ammonium Nitrate (explosive) |
| AP | antipersonnel |
| APG | Aberdeen Proving Ground |
| Ar | argon |
| ARO | Army Research Office |
| AT | antitank |
| ATP | adenosine triphosphate |
| Au | gold |
| C4 | a common variety of military plastic explosive (also know as Composition C-4) |
| CCD | charge-coupled device |
| CERDEC | Communications-Electronics Research Development and Engineering Center |
| CL | chemiluminescence |
| COTS | commercial off-the-shelf |
| CRDS | Cavity Ring-Down Spectroscopy |
| CRREL | Cold Regions Research and Engineering Laboratory |
| DARPA | Defense Advanced Research Projects Agency |
| DASA(ESOH) | Deputy Assistant Secretary of the Army (Environment, Safety, and Occupational Health) |
| DDR&E | Director of Defense Research and Engineering |
| DDT | dichlorodiphenyltrichloroethane (insecticide) |
| DHS | Department of Homeland Security |

| | |
|-----------|---|
| DLOS | direct line of sight |
| DNT | Dinitrotoluene |
| DoDD | Department of Defense Directive |
| DUSD(S&T) | Deputy Undersecretary of Defense (Science and Technology) |
| Dynamite | an explosive based on the explosive potential of nitroglycerin using diatomaceous earth as an adsorbent |
| ECD | Electron Capture Detector |
| EGDN | ethylene glycol dinitrate |
| EMI | electromagnetic induction |
| EOD | explosive ordnance disposal |
| EPFL | Ecole Polytechnique Fédérale de Lausanne (Swiss Federal Institute of Technology, Lausanne, Switzerland) |
| ERC | explosive-related compound |
| ERDC | Engineer Research and Development Center |
| ESR | Electron Spin Resonance |
| eV | electron Volts |
| FNA | Fast Neutron Analysis |
| GC | gas chromatography |
| GICHD | Geneva International Centre for Humanitarian Demining |
| GPR | ground-penetrating radar |
| HE | helium |
| HMX | high melting explosive (octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine) |
| IDA | Institute for Defense Analyses |
| IED | Improvised Explosive Device |
| IMS | ion mobility spectrometry |
| IR | infrared |
| JIEDDO | Joint Improvised Explosive Device Defeat Organization |
| JPL | Jet Propulsion Laboratory |
| JUXOCO | Joint Unexploded Ordnance Coordination Office |
| LIDAR | Laser Imaging Detection and Ranging Light Detection and Ranging |
| LIBS | Laser Induced Breakdown Spectroscopy |
| LIPS | Laser-Induced Plasma Spectroscopy |
| LMR | Lateral Migration Radiography |
| M.O.S. | Multiple Organoleptic Systems |

| | |
|-----------------|--|
| MURI | Multidisciplinary University Research Initiative |
| NAC | nitroaromatic compound |
| NAS | National Academy of Sciences |
| NASA | National Aeronautics and Space Administration |
| NG | nitroglycerin (explosive) |
| NIJ | National Institute of Justice |
| NMR | nuclear magnetic resonance |
| NO | nitric oxide |
| NO ₂ | nitrogen dioxide |
| NO ₃ | nitrate |
| NQR | nuclear quadrupole resonance |
| NRC | National Research Council |
| NRL | Naval Research Laboratory |
| NVSED | Night Vision and Electronic Sensors Director/Directorate (U.S. Army) |
| ONR | Office of Naval Research |
| OSA | optical sensor array |
| PAS | photoacoustic spectroscopy |
| PCB | polychlorinated biphenyl |
| PELAN | pulsed elemental analysis with neutrons |
| PETN | pentaerythrite tetranitrate (an explosive) |
| PFNA | pulse fast-neutron analysis |
| POC | point of contact |
| pg | picogram |
| ppb | parts per billion |
| ppq | parts per quadrillion |
| ppt | parts per trillion |
| R&D | research and development |
| RDX | Royal Demolition eXplosive (hexahydro-1,3,5-trinitro-1,3,5 triazine, which is also known as cyclonite) |
| REDCOM | Readiness Command |
| REMPI | resonantly enhanced multiphoton ionization |
| RF | radio frequency |
| RFI | radio frequency interference |
| ROC | receiver operating characteristic |
| S&T | science and technology |

| | |
|-----------|--|
| SAW | surface acoustic wave |
| SBIR | Small Business Innovation Research |
| Semtex | a general-purpose plastic explosive |
| SNL | Sandia National Laboratory |
| SNR | signal-to-noise ratio |
| SOP | semiconducting organic polymer |
| SPIE | The International Society for Optical Engineering |
| SPME | solid phase microextraction |
| SUA | Sokoine University of Agriculture |
| TATP | Triacetone Triperoxide (explosive; also known as peroxyacetone) |
| TCRP | Transit Cooperative Research Program |
| Tetryl | a sensitive explosive compound used to make detonators and explosive booster charges |
| TIR | total internal reflection |
| TNA | thermal neutron analysis |
| TNB | Trinitrobenzene |
| TNT | 2,4,6-Trinitrotoluene (explosive) |
| TOF | time-of-flight |
| TR | Thermo-Redox |
| TRL | technology readiness level |
| USACE | U.S. Army Corps of Engineers |
| USD(AT&L) | Under Secretary of Defense (Acquisition, Technology, and Logistics) |
| UV | ultraviolet |
| UXO | unexploded ordnance |
| UXOCOE | Unexploded Ordnance Center of Excellence |
| VBIED | Vehicle-borne Improvised Explosive Device |
| WES | Waterways Experiment Station |
| YPG | Yuma Proving Ground |

APPENDIX A.
SOIL TRANSPORT CODE.TXT


```

C -----
C heat7c.for -- adaptation of original heat program (AHCP11.FOR) to
C calculate temperature profiles in cylindrical
C coordinates.
C
C rvuduc, June '96
C BBalko, October 2005 adaptation to particle diffusion and convection
C I.Chappell October 2005 changes in file formats
C -----
C
C COND(K) : DIFFUSIVITY OF MATERIAL K
C (CM^2/SEC)
C DEN(K) : DENSITY OF MATERIAL K (GM/CM**3)
C CAP(K) : SPECIFIC HEAT OF MATERIAL K (1)
C LM(I,J) : CELL MATERIAL INDEX
C XB(I,J) : DIFFUSIVITY. BETWEEN CELLS (I,J) AND (I+1,J)
C ZB(I,J) : DIFFUSIVITY BETWEEN CELLS (I,J) AND (I,J+1)
C D(I,J) : DENSITY OF CELL (I,J)
C C(I,J) : SPECIFIC PARTICLE DENSITY OF CELL (I,J)
C KG CDV(I,J) : SPECIFIC PARTICLE CAPACITY OF CELL (I,J)
C KG : VOLUME OF CELL = ZH(I,J) * ZS(I,J)
C XR(I,J) : RADIAL DIMENSION OF CELL (I,J) in cm
C ZH(I,J) : AXIAL DIMENSION OF CELL (I,J) in cm
C XS(I,J) : SURFACE AREA OF RIGHT SIDE OF CELL (I,J)
C ZS(I,J) : SURFACE AREA OF TOP SIDE OF CELL (I,J)
C ZZ(I,J) : TEST MODULUS(AXIAL DIRECTION),MUST BE < 1/2
C ZX(I,J) : TEST MODULUS(RADIAL DIRECTION),MUST BE < 1
C U(I,J) : CONCENTRATION OF CELL (I,J)
C -----
C Uchem(I,J) CONCENTRATION OF CELL (I,J)ATTACHED TO SOLID
C xUchem(I,J) CHANGE IN CONCENTRATION ATTACHED TO SOLID
C Uo(I,J) : CONCENTRATION OF CELL (I,J)in previous time step
C ZVEL(I,J) VELOCITY IN Z-DIRECTION
C XVEL(I,J) VELOCITY IN X-DIRECTION
C ZQR(I,J) CHANGE IN Z-VELOCITY
C XQR(I,J) CHANGE IN X-VELOCITY
C -----
C
C KG Initial concentration for the cells is an input value
C T1 : TIME INCREMENT (seconds)
C APM T9 : Final Time (seconds)
C
C KG T : Time parameter (seconds)
C APM VART1 : Suggested first time step.
C
C KG NuM : parameter values used to dimension array easily
C APM xheat : explosive source [grams/(sec cm^3) for each cell]
C
C APM icell(i) : i'th radial cell for heat source
C
C APM jcell(i) : j'th z cell for heat source
C
C APM E1 : E1 = 0 for rectangular coor. problems; 1 for polar coor.
problems
C
C KG UEL : Temperature change due to heating in region
C KG THP1 : Start of pulse
C KG THP2 : End of pulse
C KG Y : Radial position of the cell (cm)
C APM Y1 : First Cell Position (cm)

```

```

C      NM      :  NUMBER OF MATERIALS READ IN
C      NX      :  TOTAL NUMBER OF CELLS IN RADIAL DIRECTION
C      NZ      :  TOTAL NUMBER OF CELLS IN AXIAL DIRECTION
C      XQ(I,J) :  PARTICLE TRANSFER IN RADIAL DIR.  OUT OF CELL (I,J)
C      ZQ(I,J) :  PARTICLE TRANSFER IN AXIAL DIR.  OUT OF CELL (I,J)
C APM  a5      :  Print Frequency (print after a5 time steps)
C      nprnz   :  # of selected axial cells to print
C      nprnr   :  # of selected radial cells to print
C      prnz    :  prnz(j) == 0 to enable print, 1 to disable
C      prnr    :  prnr(i) == 0 to enable print, 1 to disable
C      prnmat  :  prnmat(i,j) == 0 (no print) or 1 (print) cell (i,j)
C      prnbyR  :  print by R (1), or by Z (0)
C      nprnsets :  number of sets of columns to print (added ic 10/26/05)
C      -----

```

C\$DEBUG

```

      implicit real*8(a-h,o-z)
C
C      NuM - maximum radial array element
C      KuJ - maximum axial array element
C      MAXDIM := max(NuM, KuJ)
C
C      parameter (KuJ=150)
C      parameter (NuM=150)
C      parameter (MAXDIM=150)
C
C      MAXMAT - maximum # of materials
C      MAXSTR - maximum length of an output string
C      BASEOUTFILE - base file # for the first output file
C
C      parameter (MAXMAT=20)
C      parameter (MAXSTR=512)
C      parameter (BASEOUTFILE=25)
C
C      i/o variables
C
C      character*255      AAA
C      character*13       name(MAXMAT)
C      character*512      outtemp, outidx, outtemp2
C      character*128      infile, outfile, outinfile, outoutfile
C      character*128      utimefile(MAXDIM),outearthfile,outairfile
C      integer            setnum, El
C      integer            nprnr, nprnz
C      integer            prnr(NuM), prnz(KuJ)
C      integer            pos0, posn, posi
C      integer            nprnsets
C      double precision   tlopt
C      double precision   tvlopt
C
C      simulation variables
C
C      dimension cond(MAXMAT), den(MAXMAT), cap(MAXMAT),
1  xb(NuM,KuJ), zb(nUm,kUj), d(NuM,kUj), c(NuM, KuJ),
2  xr(nUm,kUj), zh(nUm,kUj), xs(nUm,kUj), zs(nUm,kUj),
*  xq(nUm,kUj), zq(nUm,kUj), xtbsx(nUm,kUj),
3  ztbsx(nUm,kUj), cdv(nUm,kUj), icell(100), jcell(100),
*  zz(nUm,kUj), zx(nUm,kUj), u(nUm,kUj), xx(nUm,kUj), b(nUm,kUj),
4  mxl(80), y(nUm,kUj), z(375,4), z1(375), uel(nUm,kUj), Uo(nUm,kUj),
5  zvel(nUm,kUj), xvel(nUm,kUj), zzvel(nUm,kUj), xxvel(nUm,kUj),
6  xqv(nUm,kUj), zqv(nUm,kUj), xUchem(nUm,kUj), Uchem(nUm,kUj),
7  bb(nUm,kUj), dd(nUm,kUj), xrat(MAXMAT), xads(MAXMAT),
8  yUchem(nUm,kUj), zUchem(nUm,kUj), Usoil1(nUm), Usoil(nUm),

```



```

9  Uair1(nUm), Uair(nUm)
C
    common xl(nUm), zl(nUm), lm(nUm,kUj), xz(nUm,kUj)
C
    data mx1/1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,
.      21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,
.
.      38,39,30,41,42,43,44,45,46,47,48,49,50,51,52,53,54,
.
.      55,56,57,58,59,60,61,62,63,64,65,66,67,68,69,70,71,
.
.      72,73,74,75,76,77,78,79,80/

C
C  -----
C
C  open data files
C  ('UNKNOWN' status allows existing file overwrite)
C
    write(6,*) 'Enter input filename: '
    read(5,'(A128)') infile
    write(6,*) 'Enter output filename: '
    read(5,'(A128)') outfile
    write(6,*) 'Enter data set #: '
    read(5,'(I5)') setnum
C
    outinfile = 'outin .dat'
    utimefile(1) = 'ut - .asc'
    outoutfile = 'mybaby .dat'
    outearthfile = 'earthsoil .dat'
    outairfile = 'airsoil .dat'
C$NODEBUG
    write(outinfile(6:7), '(I2.2)') setnum
    write(outoutfile(7:8), '(I2.2)') setnum
    write(utimefile(1)(7:8), '(I2.2)') setnum
    write(outearthfile(10:11), '(I2.2)') setnum
    write(outairfile(8:9), '(I2.2)') setnum
C$DEBUG
C
    open(unit=1, status='OLD', file=infile)
    open(unit=22, status='UNKNOWN', file=outinfile)
    open(unit=23, status='UNKNOWN', file='temp.dat')
    open(unit=24, status='UNKNOWN', file=outoutfile)
    open(UNIT=30, status='UNKNOWN', file=outoutfile)
    open(UNIT=31, status='UNKNOWN', file=outearthfile)
    open(UNIT=32, status='UNKNOWN', file=outairfile)
C
    ize=0
C
C  read input parameters
C
C  [NOTE:  all temperature data read in is assumed to be in deg F
C          and is automatically converted to deg C]
C
    write(22,*) '----- Kinetic Parameters -----'

C Modification by APM 3/18/98-----

c
    print*, '1'
    read(1,*) E1

    if(E1.eq.0)then

```

```

        write(22,*)'E1 = ',E1,' => rectangular coordinates problem.'
elseif(E1.eq.1)then
        write(22,*)'E1 = ',E1,' => polar coordinates problem.'
else
        write(22,*)'The value for E1 you input is an uncorect value.'
endif

read(1,*) ncellxb,ncellxe, xheat
read(1,*) ncellzb,ncellze
write(22,*) 'number of cells with heat sour = ',inumcell

C -----
        read(1,*) thp1, thp2, xhenry, concx
        write(22,*) thp1, thp2, xhenry, concx
        read(1,*) t1, t9
        write(22,*) 't1, t9 = ', t1, ', ', t9
C
C      variable t1 parameters read in, but (for now) ignored
C
        read(1,*) vart1, tlper, tlfac
        write(22,*) 'vart1, tlper, tlfac = ', vart1, tlper, tlfac
C

        write(22,*) '----- Thermo. Properties of Mat. -----'
        read(1,*) nm
        write(22,*) 'nm = ', nm
        do 140 i=1, nm
                read(1,141) name(i), cond(i), den(i),cap(i),XRAT(i),XADS(i)
                write(22,141) name(i), cond(i), den(i),cap(i),XRAT(i),XADS(i)
140      continue
141      format(1X,A13,6F10.6)
C
        write(22,*) '----- Read in cell dimensions -----'
        read(1,*) a5
        write(22,*) 'a5 = ', a5
        read(1,*) nx, nz
        write(22,*) 'nx, nz = ', nx, ', ', nz
        read(1,*) y1
        write(22,*) 'y1 = ', y1
C
        read(1,*)xl11,zl11
        write(22,*) 'Cells: '
C      read(1,*) (xl(i),i=1,nx)
        do 5010 i=1,nx
                xl(i)= xl11
5010      continue
        do 5015 j=1,nz
                zl(j)=zl11
5015      continue
        write(22,*) (xl(i),i=1,nx)
C      read(1,*) (zl(j),j=1,nz)
        write(22,*) (zl(j),j=1,nz)
C
        nx1 = nx - 1

```

```

        nz1 = nz - 1
C
C      (skip a line)
C      read(1,'(A255)') aaa
C      read(1,'(A255)') aaa
C
C      write(22,*) '----- Read in cell contents/ic -----'
142      format(1X,2I3,2x, 20I3)
143      format(1X, 20(F5.0,1X))
        do 144 j=1, nz
            read(1,*)jj, (lm(i,j),i=1,nx)
            write(22,142)j, (lm(i,j),i=1,nx)
144      continue
C
C      read particle concentration in cell
C
        do 147 j=1, nz
            read(1,*)jj, (u(i,j),i=1,nx)
C            write(22,143) (u(i,j),i=1,nx)
            write(22,*)j, (u(i,j),i=1,nx)
147      continue
C
C=====
C =====Begin New Stuff =====
C=====
C      read drift velocity in cell of water and dissolved particles
C
C      read velocity direction and magnitude
C
        read(1,*) vzdir, vzmag, vznum
        do 1147 j=1,nz
        do 1147 i=1,nx
C            read(1,*) (zzvel(i,j),i=1,nx)
            zzvel(i,j)=1.0
1147      continue
            read(1,*) vxdir, vxmag, vxnum
            do 1149 j=1,nz
            do 1149 i=1,nx
C                read(1,*) (xxvel(i,j),i=1,nx)
                xxvel(i,j)= 1.0
1149      continue
C
        do 1151 j=1,nz
        do 1151 i=1,nx
            zvel(i,j)= zzvel(i,j)*vzmag
            xvel(i,j)= xxvel(i,j)*vxmag
1151      continue
            write(22,*) vzdir, vzmag, vznum
            write(22,*) vxdir, vxmag, vxnum
C=====
        tnt= t9/t1
        nt=int(tnt)/a5
        write(30,*)nt,nx,nz
C=====
C =====End New Stuff =====
C=====
        write(22,*) '----- output parameters -----'
        read(1,*) prnByR
        write(22,*) 'prnByR = ', prnByR
        read(1,*) nprnr
        write(22,*) 'nprnr = ', nprnr
        read(1,*) (prnr(i), i=1,nprnr)
        write(22,*) 'prnr = ', (prnr(i), i=1,nprnr)

```

```

        read(1,*) nprnz
        write(22,*) 'nprnz = ', nprnz
        read(1,*) (prnz(i),i=1,nprnz)
        write(22,*) 'prnz = ', (prnz(i), i=1,nprnz)
C
        close(UNIT=1)
C
C        prepare output files
C
        outtemp = ' '
        do 145 i = 1,nx
145      outtemp = outtemp // ' '
        outidx = outtemp
        outtemp2 = outtemp
C
C
        t = 0.D0
C
C        definition of cell thermal properties
C
C
        do 5175 i = 1,nx
            do 5175 j = 1,nz
                xUchem(i,j)=0.0
                Uchem(i,j)=0.0
5175      continue
C
C
C
        do 175 i = 1,nx
            do 175 j = 1,nz
                ll = lm(i,j)
                b(i,j) = cond(ll)
                d(i,j) = den(ll)
                c(i,j) = cap(ll)
                bb(i,j)= xrat(ll)
                dd(i,j)= xads(ll)
175      continue
C
C        definition of cell geometry
C
        do 170 i = 1,nx
            do 170 j = 1,nz
                xr(i,j) = xl(i)
                zh(i,j) = zl(j)
170      continue
C
        write(22,180)
180      format(1X,/, '      NM  NX  NZ      A5      T9')
        write(22,190) NM,NX,NZ,A5,T9
190      format(1X,3I5,2E10.2)
        write(22,200) T1
200      format(1H ,/, ' T1=',E10.2)
C
C        calculation of heat transfer cell parameters
C
C
C        xx(i,j) = distance between cell centers in the radial direction
        P1=3.1415926535897932D0
        do 210 i = 1,nx1
            do 210 j = 1,nz
                xx(i,j)=(xr(i,j) + xr(i+1,j))/2.0
210      continue
C

```

```

C      xz(i,j) = distance between cell centers of in the axial direction
      do 212 i = 1,nx
        do 212 j = 1,nz1
          xz(i,j) = (zh(i,j) + zh(i,j+1))/2.0
212    continue
C
C      thermal conductivity between cells
C
      do 220 i = 1,nx1
        do 220 j = 1,nz
          xb(i,j)=(xr(i,j)+xr(i+1,j))/(xr(i,j)/b(i,j)+xr(i+1,j)/b(i+1,j))
220    continue
C
      do 222 i = 1,nx
        do 222 j = 1,nz1
          zb(i,j)=(zh(i,j)+zh(i,j+1))/(zh(i,j)/b(i,j)+zh(i,j+1)/b(i,j+1))
222    continue
C
C      calculation of surface area of cells
C
      do 225 j = 1,nz
        y(1,j)=y1 + xr(1,j)/2.0
225    continue
C
      do 230 i = 2,nx
        DO 230 j = 1,nz
230      y(i,j)=y(i-1,j)+(xr(i,j)+xr(i-1,j))/2.0
C
      do 240 I = 1,nx
        do 240 J = 1,nz
          xs(i,j)=(P1*(2.*y(i,j)+xr(i,j))*zh(i,j))*E1
          zs(i,j)=(2.*P1*y(i,j)*xr(i,j))*E1
          cdv(i,j)=c(i,j)*d(i,j)*zh(i,j)*zs(i,j)
240    continue
C
      tlopt = 1.0e10
      tvlopt = 1.0e10
      do 260 i = 1,nx1
        do 260 j = 1,nz
          w = 1.d0 / cdv(i,j) + 1.d0 / cdv(i+1,j)
          xtbsx(i,j)=t1 * xb(i,j) * xs(i,j) / xx(i,j)
          zx(i,j) = 4.d0 * w * xtbsx(i,j)

          tttt = .125*xx(i,j)/xb(i,j)/xs(i,j)/w
          if( tttt.lt.tlopt ) tlopt = tttt
260    continue
C
      do 262 i = 1,nx
        do 262 j = 1,nz1
          w=1.d00/cdv(i,j)+1.d00/cdv(i,j+1)
          ztbsx(i,j)=t1*zb(i,j)*zs(i,j)/xz(i,j)
          zz(i,j)=4.d00*w*ztbsx(i,j)

          tttt = .125*xz(i,j)/zb(i,j)/zs(i,j)/w
          if( tttt.lt.tlopt ) tlopt = tttt
262    continue
C
C
C=====
C =====Begin New Stuff =====
C=====
      do 1262 i=1,nx
        do 1262 j=1,nz

```

```

        tttvx = vxnum/(xs(i,j)*xvel(i,j))
        if( tttvx.lt.tvlopt)  tvlopt = tttvx
1262      continue
        write(6,263) 'interim tvlopt (x)', tvlopt
        write(22,263) 'interim tvlopt (x)', tvlopt
        do 1264 i=1,nx
        do 1264 j=1,nz
            tttvz = vznum/(zs(i,j)*zvel(i,j))
            if( tttvz.lt.tvlopt)  tvlopt = tttvz
1264      continue
        write(6,263) 'interim tvlopt (z)', tvlopt
        write(6,263) 'interim tttt', tttt
        write(6,263) 'interim tlopt', tlopt
        write(22,263) 'interim tvlopt (z)', tvlopt
        write(22,263) 'interim tttt', tttt
        write(22,263) 'interim tlopt', tlopt
        if( tvlopt.lt.tttt) tttt=tvlopt

C=====
C =====End New Stuff =====
C=====
C
C
        if( (vart1.gt.0).and.(t1.lt.tttt) ) then
            write(6,263) 't1 = ', t1
            write(6,263) 'a better t1 might be ', tlopt
        else
            if( t1.gt.tttt ) then
                write(6,*) 'WARNING: t1 may be too big!'
                write(6,263) 'optimal = ', tlopt
                write(22,*) 'WARNING: t1 may be too big!'
                write(22,263) 'optimal = ', tlopt
            endif
        endif
        write(6,263) 't1 =', t1
        write(6,263) 'tttt=', tttt
        write(22,263) 't1 =', t1
        write(22,263) 'tttt=', tttt
        write(6,263) 'extra optimalv= ',tvlopt
        write(6,263) 'extra optimal = ',tlopt
        write(22,263) 'optimalv = ', tvlopt
        write(22,263) 'optimal= ', tlopt
263      format(1X, A25, e10.4)
C
        do 265 i = 1,nx
265          zz(i,nz) = 0.d00
        do 266 j = 1,nz
266          zx(nx,j) = 0.d00
C
C      calculate total initial heat
C
        q0 = 0.0
        do 149 i = 1,nx
            do 149 j = 1,nz
                q0 = q0 + u(i,j)*cdv(i,j)
149      continue
        write(6,*) 'initial heat: ', q0
C
C      print cell properties
C
        write(22,600)
        write(22,605)
600      format(27X, 'Material Properties',/)

```

```

605   format(4X,'MATERIAL(I)',3X,'CONDUCTIVITY',3X,'DENSITY',3X,
1    'SPECIFIC HEAT ',/)
C
      do 610 i = 1,nm
610       write(22,615) i,name(i),cond(i),den(i),cap(i)
615   format(1X,I5,1X,A10,2X,F9.6,2X,F9.6,6X,F9.6)
      write(22,670)
670   format(1X,/,10X,'CALORIMETER GEOMETRY ',/)
      write(22,671) (mx1(i),i=1,nx)
671   format(9X,'ZL',/,80(I4,2X))
      do 672 j=1,nz
          write(22,675) j,zl(j),(lm(i,j),i=1,nx)
672   continue
C KG   Write the XL values
      write(22,673) (xl(i), i=1,nx)
673   format(9X,80(F5.3,1X))
675   format(2X,I4,3X,F6.4,80(I4,2X))
C
C       prepare output temperature file
C
C$NODEBUG
C       nprnsets = int(nprncols/35)+1

C       if( prnbyr .eq. 0 ) then
C           write(utimefile(1)(3:3), '(A1)') 'z'
C           nprnfiles = nprnz
C           nprncols = nprnr
C       else
C           write(utimefile(1)(3:3), '(A1)') 'r'
C           nprnfiles = nprnr
C           nprncols = nprnz
C       endif

C       write(utimefile(1)(4:5), '(I2.2)') 1
C       do 831 i = 2, nprnfiles*nprnsets
C           utimefile(i) = utimefile(1)
C           if( prnbyr.eq.0 ) then
C               write(utimefile(i)(4:5), '(I2.2)') prnz(i)
C           else
C               write(utimefile(i)(4:5), '(I2.2)') prnr(i)
C           endif
C       831   continue

C       a header line for the files
C
C       do 830 i = 1, nprncols
C           nsets = int((i-1)/35)
C           pos0 = (i-1)*7 + 1 - nsets*35*7
C           posn = i*7 - nsets*35*7
C           if (prnbyr.eq.0) then
C               posi = prnr(i)
C           else
C               posi = prnz(i)
C           endif
C           write(outidx(pos0:posn),835) posi
C           if (posn.ge.(7*35)) then
C               do 814 j = 1, nprnfiles
C                   k=(nsets*nprnsets)+j
C                   open(UNIT=25, STATUS='UNKNOWN', FILE=utimefile(k))
C                   write(25, 837) 'time', outidx
C                   close(UNIT=25)
C                   write(24, 836) outidx
C               814   continue

```

```

C          endif
C 830      continue
C          835      format(2X,I3,2X)
C          836      format(1X,'I= ',A512)
C          837      format(1X,A7,A512)
C
C          open each output file and output header
C
C$DEBUG
C
C          Write the cell temperature data to a separate
C          file for plotting later 5-31-88
C
C          Write the radial distances for the cells
C          do 50 i = 1,nx
C              yout = y(i,1)
C * 1.0E4
C              write(24,804) yout
C          804      format(1X,F7.4)
C          50      continue
C              write(24,805)
C          805      format(1X,16X,'CELL TEMPERATURES',/)
C
C
C
C          klim=int(a5+.5)
C          write(24,676)
C          676      format(2X,'TIME')
C
C          end of initialization
C          print out "zeroth" iteration
C
C          go to 380
C
C          beginning of main loop
C
C          340      continue
C              kt = 0
C          345      continue
C              kt = kt + 1
C
C          calculation of concentration rise in cell 1
C          due to leak of explosive from mine
C          Calculate the UEL(I,J) values
C
C          if((t.ge.thp1).and.(t.le.thp2)) then
C              do 342 i = 1,nx
C                  do 341 j = 1,nz
C                      uel(i,j) = 0.0
C APM 3/18/98 Increase the temperature as the result of a heat source.
C
C              do iii=1,inumcell
C
C                  if ((i.eq.icell(iii)).and.(j.eq.jcell(iii)))then
C                      uel(i,j) = xheat(iii) * t1
C
C                      print*,uel(i,j)
C                  end if
C
C              enddo
C
C              print*, 'i,j',i,j
C          341      continue

```



```

342      continue
      endif

      do 5030 i=ncellxb,ncellxe
      do 5030 j=ncellzb,ncellze
          uel(i,j)= xheat*t1
5030  continue
C      enddo
C
C      calculation of heat transfer xq(i,j), zq(i,j) between cells
C      and new temperatures u(i,j)
C
      do 350 i = 1,nx1
          do 350 j = 1,nz
              xq(i,j)=(xb(i,j)*xs(i,j)/xx(i,j))*(u(i,j)-u(i+1,j))*t1

350  continue
C
      do 352 i = 1,nx
          do 352 j = 1,nz1
              zq(i,j)=(zb(i,j)*zs(i,j)/xz(i,j))*(u(i,j)-u(i,j+1))*t1

352  continue
C
      do 362 i = 2,nx1
          do 360 j = 2,nz1
              u(i,j)=u(i,j)+(xq(i-1,j)-xq(i,j)+zq(i,j-1)-zq(i,j))/cdv(i,j)
360  continue
              u(i,1) = u(i,1)+(xq(i-1,1)-xq(i,1)-zq(i,1))/cdv(i,1)

              u(i,nz)=0.
C              u(i,nz) = u(i,nz)+(xq(i-1,nz)-xq(i,nz)+zq(i,nz1))/cdv(i,nz)
362  continue
              do 364 j = 2,nz1
                  u(1,j) = u(1,j)+(-xq(1,j)+zq(1,j-1)-zq(1,j))/cdv(1,j)
                  u(nx,j) = u(nx,j)+(xq(nx1,j)+zq(nx,j-1)-zq(nx,j))/cdv(nx,j)
364  continue
                  u(1,1) = u(1,1)+(-xq(1,1)-zq(1,1))/cdv(1,1)

                  u(nx,1) = u(nx,1)+(xq(nx1,1)-zq(nx,1))/cdv(nx,1)

              u(nx,nz)=0.

              u(1,nz)=0.
C              u(nx,nz) = u(nx,nz)+(xq(nx1,nz)+zq(nx,nz1))/cdv(nx,nz)
C              u(1,nz) = u(1,nz)+(-xq(1,nz)+zq(1,nz1))/cdv(1,nz)
C
C      temperature rise in cell due to reaction
C
C KG
      do 366 i = 1,nx
          do 365 j = 1,nz
              u(i,j) = u(i,j) + uel(i,j)
365  continue
366  continue
C=====
C =====Begin New Stuff =====
C=====
C
C      calculation of particle transfer xqv(i,j), zqv(i,j) between cells
C      due to drift velocity (POSITIVE) and new concentrations u(i,j)
C
      if(vzdir.gt.0.and.vxdir.gt.0) then

```

```

C
1351  continue
      do 1350 i = 1,nx1
        do 1350 j = 1,nz
          xqv(i,j)=xs(i,j)*u(i,j)*xvel(i,j)*t1

1350  continue
C
      do 1352 i = 1,nx
        do 1352 j = 1,nz1
          zqv(i,j)=zs(i,j)*u(i,j)*zvel(i,j)*t1

1352  continue
C
      do 1362 i = 2,nx1
        do 1360 j = 2,nz1
          u(i,j)=u(i,j)+(xqv(i-1,j)-xqv(i,j)+zqv(i,j-1)-zqv(i,j))
1360  continue
          u(i,1) = u(i,1)+(xqv(i-1,1)-xqv(i,1)-zqv(i,1))

          u(i,nz)=0.
          u(i,nz) = u(i,nz)+(xqv(i-1,nz)-xqv(i,nz)+zqv(i,nz1))
1362  continue
          do 1364 j = 2,nz1
            u(1,j) = u(1,j)+(-xqv(1,j)+zqv(1,j-1)-zqv(1,j))
            u(nx,j) = u(nx,j)+(xqv(nx1,j)+zqv(nx,j-1)-zqv(nx,j))
1364  continue
          u(1,1) = u(1,1)+(-xqv(1,1)-zqv(1,1))

          u(nx,1) = u(nx,1)+(xqv(nx1,1)-zqv(nx,1))

          u(nx,nz)=0.

          u(1,nz)=0.
          u(nx,nz) = u(nx,nz)+(xqv(nx1,nz)+zqv(nx,nz1))
          u(1,nz) = u(1,nz)+(-xqv(1,nz)+zqv(1,nz1))

1365  continue
      else
C=====
C =====End New Stuff =====
C=====
C
      do 5550 i=1,nx
        do 5550 j=1,nz
          Uo(i,j)=u(i,j)
5550  continue
C=====
C =====Begin New Stuff =====
C=====
C
      if(vzdir.lt.0.and.vxdir.lt.0) then
C      calculation of particle transfer xqv(i,j), zqv(i,j) between cells
C      due to drift velocity (NEGATIVE) and new concentrations u(i,j)
C      no transfer out of (i,1) to left
      do 2350 i = 1,nx1
        do 2350 j = 1,nz
          xqv(i,j)=xs(i,j)*u(i,j)*xvel(i,j)*t1

2350  continue
C
      do 2352 i = 1,nx
        do 2352 j = 1,nz1

```

```

                zqv(i,j)=zs(i,j)*u(i,j)*zvel(i,j)*t1

2352  continue
C
      do 2362 i = 2,nx1
        do 2360 j = 2,nz1
          u(i,j)=u(i,j)+(xqv(i+1,j)-xqv(i,j)+zqv(i,j+1)-zqv(i,j))
C          u(i,j)=u(i,j)+(xqv(i+1,j)-xqv(i,j)+zqv(i,j+1))
2360      continue
C          u(i,1) = u(i,1)+(xqv(i+1,1)-xqv(i,1))

          u(i,nz)=0.
C          u(i,nz) = u(i,nz)+(xqv(i+1,nz)-xqv(i,nz)-zqv(i,nz))
2362  continue
      do 2369 i=2,nx
        u(i,1) = u(i,1)+(xqv(i+1,1)-xqv(i,1)+zqv(i,2))
2369  continue
      do 2364 j = 2,nz1
        u(1,j) = u(1,j)+(-xqv(1,j)+xqv(2,j)+zqv(1,j+1)-zqv(1,j))
        u(nx,j) = u(nx,j)+(-xqv(nx,j)+zqv(nx,j+1)-zqv(nx,j))
2364  continue
C      u(1,1) = u(1,1)+(-xqv(1,1)-zqv(1,1)+xqv(2,1)+zqv(1,2))
      u(1,1) = u(1,1)+(-xqv(1,1)+xqv(2,1)+zqv(1,2))
      u(nx,1) = u(nx,1)+(-xqv(nx,1)-zqv(nx,1)+zqv(nx,2))

      u(nx,nz)=0.

      u(1,nz)=0.
C      u(nx,nz) = u(nx,nz)+(-xqv(nx,nz)-zqv(nx,nz))
C      u(1,nz) = u(1,nz)+(-xqv(1,nz)-zqv(1,nz)+xqv(2,nz))
      endif
      endif
4365  continue
C=====
C =====End New Stuff =====
C=====
C
C
C
C
C=====
C =====Begin New Stuff =====
C=====
C
C      Adsorption of molecules by soil particles adding to Uchem(i,j) and
C      reduction of cell concentration U(i,j)
      do 3366 i = 1,nx
        do 3365 j = 1,nz
          xUchem(i,j)=dd(i,j)*t1*U(i,j)
3365      continue
3366      continue

      do 2366 i = 1,nx
        do 2365 j = 1,nz
          Uchem(i,j)=Uchem(i,j)+xUchem(i,j)
          u(i,j) = u(i,j) - xUchem(i,j)

2365      continue
2366      continue
C=====
C=====End New Stuff=====
C=====

```

```

C=====
C=====Begin New Stuff=====
C=====
C      Breakup of molecules by half life and
C      reduction of cell concentration U(i,j)
      do 5366 i = 1,nx
        do 5365 j = 1,nz
          yUchem(i,j)=bb(i,j)*t1*U(i,j)
5365      continue
5366      continue

      do 6366 i = 1,nx
        do 6365 j = 1,nz

          u(i,j) = u(i,j) - yUchem(i,j)

6365      continue
6366      continue

C=====
C=====End New Stuff =====
C=====
C
C
C      temperature change of sensor
C
C
C      write(22,2605)

2605      format(4X,'time',6X,'j',10X,'Uo(1,j)',6X,'xqv(2,j)',3X,
1      'zqv(1,j+1)',6X,'-zqv(1,i)',10X,'U(1,j) ',/)
C
      do 2610 j = 1,nz
2610      write(22,2615)t,j,Uo(1,j),xqv(2,j),zqv(1,j+1),-zqv(1,j),U(1,j)
2615      format(1X,F9.6,1X,I5,2X,F16.6,2X,F9.6,2X,F9.6,2X,F16.9,2X,F16.6)

      t = t + t1
      if (kt.lt.klim) go to 345
C
C      print temperature of cells
C
380      CONTINUE
C
C      print time
C
      write(6,812) T
      write(24,813) T, T1
812      format(1X, 'T= ', e10.4)
813      format(1X, 'T= ', e10.4, e10.4)
C
C      print temperature; first build string which
C      represents the line to be written
C
      write(30, *) t

      do 9001 j = 1, nz
        write(30, 7143) (u(i,j), i=1,nx)
9001      continue
C

```

```

C      =====Begin New Computatin 3/11/05 =====
C
      do 9003 i=1,nx
        uairl(i)=xhenry*u(i,1)
        u(i,1)=u(i,1)-uairl(i)
9003  continue
C      Compute real concentrations in air boundary layer
C      Compute real concentrations in soil surface layer
        write(31, *) t
        write(32, *) t
        do 9005 i=1,nx
          usoil(i)=concX*u(i,1)/100
          uair(i)=uairl(i)*concX/100
9005  continue
        write(31, 7145) (usoil(i), i=1,nx)
        write(32,7145) (uair(i), i=1,nx)
C
C      End Compute real concentrations in air boundary layer and soil bl
C
C      =====End New Computation=====
C
7143  format(1X, 20(F7.3,2X))
7145  format (1X,20(E10.2,2x))
C      do 681 f = 1, nprnfiles
C        if( prnbyr.eq.0 ) then
C          k = prnz(f)
C        else
C          k = prnr(f)
C        endif
C
C      do 680 i = 1, nprncols
C        nsets = int((i-1)/35)
C        j = this row, k = this file
C        if( prnbyr.eq.0 ) then
C          j = prnr(i)
C          uout = u(j,k)
C        else
C          j = prnz(i)
C          uout = u(k,j)
C        endif
C        pos0 = (i-1)*7 + 1 - nsets*35*7
C        posn = i*7 - nsets*35*7
C$NODEBUG
C        write(outtemp(pos0:posn),690) uout
C$DEBUG
C        if (posn.ge.(7*35)) then
C          l = f+nprnsets*nsets
C          write(24, 695) k, outtemp
C          open(UNIT=25, ACCESS='APPEND',STATUS='UNKNOWN',
FILE=utimefile(l))
C          write(25, 696) t, outtemp
C          close(UNIT=25)
C        endif
C      680  continue
C      681  continue
690  format(F7.1)
695  format('U', I2.2, A512)
696  format(e10.4, A512)
C
C
C

```

```

        IZT = IZT + 1
        Z1(IZT) = T
C
C KG Calculate the midpoint of the vertical distance
C
        MIDPT = (FLOAT(NZ) + 1.0) / 2.0
        Z(IZT,1) = U(1,MIDPT)
        Z(IZT,2) = U(NW1,MIDPT)
        Z(IZT,3) = U(NW1+1,MIDPT)
        Z(IZT,4) = U(NW2,MIDPT)
C
C back to beginning of loop
C
        if(t.lt.t9) go to 340
C
C
C
        WRITE(22,640)
640  FORMAT(1X,/,/, '      EFFECTIVE CELL PROPERTIES',/)
        WRITE(22,645)
645  FORMAT(2X,'CELL',4X,'MATERIAL',3X,'CONDUCTIVITY',9X,'DIMENSION',
1    10X,'SURFACE AREA',6X,'MODULUS',7X,'VOLUME',7X,'HEAT INPUT'/)
        WRITE(22,650)
650  FORMAT(2X,'(I,J)',6X,'LM',7X,'XB',6X,'ZB',6X,'XR',6X,'ZH',6X,
1    'Y',7X,'XS',6X,'ZS',6X,'ZX',6X,'ZZ',6X,'ZS x ZH',6X,
2    'XH1 & XH2'/)
        WRITE(22,651)
651  FORMAT(1X,'-----',5X,'--',5X,'-----',2X,
1    '-----',2X,'-----',2X,
2    '-----',3X,'-----',6X,'-----')
        DO 655 I=1,NX
        DO 655 J=1,NZ
            XRM = XR(I,J)
C * 1.0E4
            ZHM = ZH(I,J)
C * 1.0E4
            YM = Y(I,J)
C * 1.0E4
            XSM = XS(I,J)
C * 1.0E8
            ZSM = ZS(I,J)
C * 1.0E8
C KG 9-23-88 Calculate and print the volume of the cell
        VOLUM = ZSM * ZHM
        WRITE(22,660) I,J,LM(I,J),XB(I,J),ZB(I,J),XRM,
1    ZHM,YM,XSM,ZSM,ZX(I,J),ZZ(I,J),VOLUM,UCL(I,J)
655  CONTINUE
660  FORMAT(1X,'( ',I2,' ', ',I2,' )',5X,I2,5X,E7.2,8(1X,e7.2),
1    3X,E7.2,4X,E7.2)

        ZDIFF =0.0
        WRITE(23,993) Z1(1),Z(1,1),ZDIFF,Z(1,2),Z(1,3),Z(1,4)
        WRITE(6,*)'IZT= ',IZT
        DO 992 I=2,IZT
            ZDIFF = Z(I,1) - Z(I-1,1)
            WRITE(23,993) Z1(I),Z(I,1),ZDIFF,Z(I,2),Z(I,3),Z(I,4)
992  continue
993  format(1X,E10.4,1X,5(1X,E11.5))
C
C calculate total final heat
C
        qf = 0.0
        do 148 i = 1,nx

```

```

        do 148 j = 1,nz
            qf = qf + u(i,j)*cdv(i,j)
148      continue
        write(6,*) 'q0, qf = ', q0, qf
        write(22,*) 'q0, qf = ', q0, qf
        close(UNIT=22)
        close(UNIT=23)
        close(UNIT=24)
        stop
    end
C
C eof
C

```


APPENDIX B. CHEMICAL VAPOR AND SOLID PARTICULATE EXPLOSIVE DETECTION TECHNOLOGIES

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DATA SHEET B-1. BIOLOGICAL SYSTEMS: BEES

| | |
|---|--|
| Description of Technology | Bees trained to associate explosive vapors with food are used to detect mines. They swarm over land mines and their flight patterns are tracked by Light Detection and Ranging (or Laser Imaging Detection and Ranging) (LIDAR). |
| Standalone Capability | Bees plus LIDAR and tracking software. |
| Sample Collection Method | Bees fly over land and congregate over mines. |
| Compounds Detected | Theoretically, bees can be trained for all explosives. Explosives released from mines and vapor pressure are limiting factors (TNT, C4, TATP compounds tested). |
| Sensitivity/Selectivity | Potential parts per trillion (ppt) to parts per quadrillion (ppq). Field trials at parts per billion (ppb) and ppt vapor concentrations of 2,4-DNT showed: (a) Detection probability of 97–99 percent (b) False positive 1.0–2.5 percent (c) False negative <1 percent. |
| Measurement Time | Depends on distance and explosive density. |
| Complexity of Use/ Training Requirements | 1 to 2 days to train bees using Pavlovian training techniques. |
| Size and Portability of Equipment | – |
| Maturity | Still in university research. |
| Affordability Issues | \$100 for beehive plus laser and tracking electronics. |
| Safety Issues | Bee stings. |
| Reliability/False Alarm | 97 percent accuracy when small (not defined) traces of vapor present; 1 percent missed when passing over a mine. Testing procedures not well documented. |

BACKGROUND

The use of bees is analogous to using dogs for mine clearance; however, a colony of tens of thousands of bees can be trained in about 1 hour to fly over and search a field for explosives, does not require a leash, and will not set off any mines. Like dogs, bees can be trained to search for either the odors of individual explosives or suites of these chemicals. Initial tests indicate that bees are capable of detecting these odors at concentrations below those detectable by most instruments.

Bees approach, if not match, the odor sensitivity of dogs (i.e., low ppt to ppq and possibly lower). Field trials with honeybees at ppb and ppt vapor concentrations of 2,4-DNT (a residue in military-grade TNT) showed a detection probability of 97–99 percent. Researchers calculated a 1.0–2.5 percent probability of false positive, and less than 1 percent probability of false negative, based on three different statistical sampling strategies (Refs. 1, 2). Calculated receiver operating characteristic (ROC) curves for 10 ppb through 0.001 ppb indicated that for doses higher than 0.01 ppb (10 ppt), the bee system behaves like a very fine-tuned, nearly ideal, detector. In addition, bees have mop-like, electrostatically charged hairs that enable them to bring back to their colonies samples of explosive chemicals as well as biological agents and other harmful materials.

TECHNICAL ISSUES

- Efficient training of bees
- Selecting bees with high olfactory responses

- Useful time limited to daytime and fair weather
- Landscape needs to be flat and preferably without reflectors like houses and trees.

REFERENCES

- Block, M., R. Medina, and R. Albanese. Analysis of data determining whether European honey bees can detect DNT. Air Force Research Laboratory. Technical Report to DARPA (in progress).
- Rodacy, Philip J., Susan Bender, Jerry Bromenshenk, Colin Henderson, and Gary Bender. August 2002. Training and deployment of honeybees to detect explosives and other agents of harm. In Proceedings of SPIE, Volume 4742, *Detection and remediation technologies for mines and minelike targets VII*, eds. Thomas Broach, Russell S. Harmon, and Gerald J. Dobeck, 474–481.

DATA SHEET B-2. BIOLOGICAL SYSTEMS: CANINES

| | |
|---|--|
| Description of Technology | Dogs are used to detect explosive residues and materials because of their exceptional olfactory sensitivity. |
| Standalone Capability | Yes. |
| Sample Collection Method | Vapor (unknown). |
| Compounds Detected | All explosive materials known. |
| Sensitivity/Selectivity | Highest: few ppb to 500 ppt. |
| Measurement Time | Detection: seconds to min.; refresh rate: duty cycle is 40 to 60 min. |
| Complexity of Use/ Training Requirements | High—must train trainer(s) and dog(s). |
| Size and Portability of Equipment | Human trainer and dog. |
| Maturity | Very mature. |
| Affordability Issues | \$5,000–\$10,000 initial \$6,000–\$12,000 training \$1,500–\$2,000 food and medical per year |
| Safety Issues | Health of dog. |
| Reliability/False Alarm | Reliable. |

BACKGROUND

Dogs have been used for years to detect objects and substances because of their excellent sense of smell. Even though the complete science of how a dog's nose works and is able to detect very small amount of explosives is still under investigation, practically speaking, a dog's nose is one of the best systems for explosives detection.

TECHNICAL ISSUES

Dogs need constant interaction with a human trainer to stay focused on their task. Dogs tire of the task and are typically rotated each half hour to maintain a high level of performance.

DATA SHEET B-3. BIOLOGICAL SYSTEMS: IMMUNOCHEMICAL

| | |
|---|---|
| Description of Technology | Specifically grown antibodies that bond to chosen molecules are used to detect explosive compounds. |
| Standalone Capability | Yes. |
| Sample Collection Method | Vapor and particle. |
| Compounds Detected | Any molecule that an antibody can be grown to bind to. |
| Sensitivity/Selectivity | Sub ppm of TNT, RDX, and PETN claimed; high – one explosive-related compound (ERC) per assay |
| Measurement Time | Measurement time: < 1 min; analysis time: minutes (depends on system). |
| Complexity of Use/ Training Requirements | Complex to build; moderate-to-easy to use. |
| Size and Portability of Equipment | Still in the lab. |
| Maturity | Still in the lab. |
| Affordability Issues | Under consideration. |
| Safety Issues | None. |
| Reliability/False Alarm | Moderate for chemicals systems designed to detect. |

BACKGROUND

The use of immunochemical sensors is a new technology that extends from the recent advances in biochemical technology. Antibodies designed to bind with a specific molecule are used to detect the presence of explosive contained materials. Once the antibody binds to the appropriate molecule, a property of the antibody that can be measured (e.g., optical transmittance or fluorescence) is changed.

TECHNICAL ISSUES

This technology is still in development at the laboratory level.

DATA SHEET B-4. BIOLOGICAL SYSTEMS: PLANTS

| | |
|---|---|
| Description of Technology | Using a transgenic plant bioindicator implanted in the annual weed Thale Cress (<i>Arabidopsis thaliana</i>) that detects NO ₂ from buried land mines by changing color from green to red. |
| Standalone Capability | Yes. |
| Sample Collection Method | As long as the explosive vapor can reach the plant roots, the observation is visual color change. |
| Compounds Detected | Nitrogen dioxide (NO ₂). |
| Sensitivity/Selectivity | Limited to the detection of NO ₂ . Work progressing on other compounds. |
| Measurement Time | 3 to 5 weeks for growth of plants in search area. Fast observation after this period. |
| Complexity of Use/ Training Requirements | Not difficult. Nondesert; anywhere weeds can grow. |
| Size and Portability of Equipment | Primitive planting techniques. |
| Maturity | Just turned commercial in 2004. |
| Affordability Issues | – |
| Safety Issues | – |
| Reliability/False Alarm | – |

BACKGROUND

Danish scientists have made a scientific discovery that has significant humanitarian and environmental potential. They have shown how to produce plants that change color in the presence of specific compounds within the soil, opening the way for the first bomb and land mine detection plant.

The technology is based on the genetic engineering of the plant Thale Cress (*Arabidopsis thaliana*). This plant has several advantages in developing this mine detection system. For example, it is naturally self pollinating, and the plants developed by the Danish company Aresa Biodetection are conditionally fertile so that they are male-sterile, enabling the growth of these plants to be strictly controlled.

Aresa Biodetection (<http://www.aresa.dk/>) has been working on the plant for several years but has now developed the plant to the point where it is becoming a commercially viable biodetection system and can change color from green to red within 3 to 5 weeks of growth.

This technology is being developed to detect explosives present in land mines and unexploded ordnance (UXO) in soil and to detect and remove heavy metals in polluted soil. The invention may significantly speed the removal of land mines and UXO in cultivatable areas to permit the subsequent use of these cleared areas for agriculture to maximize socio-economic benefits. The plants will be tested and gradually introduced in land mine and UXO removal operations as the technology matures.

TECHNICAL ISSUES

- How to design this plant (Thale Cress) or other plants to detect other explosive compounds
- Increase the growth rate for faster response.

REFERENCES

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DATA SHEET B-5. BIOLOGICAL SYSTEMS: RATS

| | |
|---|---|
| Description of Technology | Trained rats are used to detect explosives/mines. |
| Standalone | Yes. |
| Sample Collection Method | Rat on a leash between two trainers sweeps a field. |
| Compounds Detected | All compounds for which the rat has been trained. |
| Sensitivity/Selectivity | High; shown to be able to locate plastic and metal mines and UXO. "A reliable detection up to the range of 10 femtograms of TNT/L of air or 1×10^{-3} ppt of headspace vapour" (Ref. 1). |
| Measurement Time | Direct detection: 30 min/100 m ² . |
| Complexity of Use/ Training Requirements | 8–12 mos to train. |
| Size and Portability of Equipment | One African Giant Poached rat (weight 0.7–1.5 kg, size 30–40 cm plus 40-cm tail; handlers and equipment. |
| Maturity | Technology used in Tanzania, Africa. |
| Affordability Issues | < \$2,000 per rat. |
| Safety Issues | This is a safe technology because rats too light to set off mines and trainers are in previously determined safe lanes. |
| Reliability/False Alarm | – |

BACKGROUND

Rats have not been used for a long time to detect objects and substances even though it was suspected for a long time that they have an excellent sense of smell. The reason could lie in the human's disgust of rats and the rat's behavior. In the 1986–1990 time frame, the U. S. Army contracted with San Diego State University to investigate the use of rats to detect land mines. Bart Weetjens, founder of Apopo, proposed the idea to use trained rats to detect land mines in Africa and the well-known animal scientist Jane Goodall supported the idea.

Apopo is a Belgian research organization whose overall objectives are to develop a low-priced methodology for efficient detection of land mines and UXO, to facilitate a reduction in the number of mine victims, and to create mine-free land in post-war countries. In 2000, Apopo established its premises and training area at the Sokoine University of Agriculture (SUA), in Morogoro, Tanzania.

Large-pouched African rats for explosives detection are now being used in field, with great success. Even though the complete science of how a rat's nose works and is able to detect very small amount of explosives is still under investigation, practically speaking, a rat's nose (much like a dog's nose) is one of the best systems for explosives detection. The advantage of using rats vs. using dogs is that they are much lighter (do not set off mines) and take less time to train. However, like dogs, they become attached to the trainer and work best with the same one.

TECHNICAL ISSUES

Short life spans. Maintaining appropriate training and effectiveness.

REFERENCES

1. Apopo International. Vapour detection technology. <http://www.apopo.org/newsite/content/index.htm>

DATA SHEET B-6. BIOLUMINESCENCE

| | |
|---|---|
| Description of Technology | Bioluminescence is the emission of light by a living organism because of a reaction in which chemical energy is converted into light. Bioluminescence is generated by an enzyme-catalyzed reaction, in which the pigment luciferin is oxidized by an enzyme luciferase. Adenosine triphosphate (ATP) ¹ is present in most cases. |
| Standalone | – |
| Sample Collection Method | Suspected explosive samples are placed in a detection module where the samples are exposed to enzymes. |
| Compounds Detected | TNT. |
| Sensitivity/Selectivity | – |
| Measurement Time | Minutes. |
| Complexity of Use/ Training Requirements | Laboratory Instrument. |
| Size and Portability of Equipment | Laboratory instrument. Miniaturization is possible. |
| Maturity | Laboratory Instrument. |
| Affordability Issues | None. |
| Safety Issues | – |
| Reliability/False Alarm | – |

BACKGROUND

Bioluminescence is a form of luminescence. Less than 20 percent of the light generates thermal radiation. Bioluminescence is not a form of fluorescence, phosphorescence, or refracted light. Approximately 90 percent of deep sea marine life is estimated to produce bioluminescence. Most bioluminescence occurs in the blue and green spectrum. Non-marine bioluminescence occurs in fireflies and New Zealand glow worms. Other insects also demonstrate bioluminescent capabilities.

TECHNICAL ISSUES

Detection times on the order of 20 min or longer would preclude some possible applications for UXO detection.

¹ ATP is considered by biologists to be the energy currency of life. It is the high-energy molecule that stores the energy we need to do just about everything we do. It is present in the cytoplasm and nucleoplasm of every cell, and, essentially, all the physiological mechanisms that require energy for operation obtain it directly from the stored ATP

DATA SHEET B-7. CAVITY RING-DOWN SPECTROSCOPY (CRDS)

| | |
|---|--|
| Description of Technology | A sample vapor enters an optical resonator with high reflectivity mirrors. Light is allowed into the cavity, and its decay rate is measured to determine the presence of explosives. |
| Standalone | – |
| Sample Collection Method | – |
| Compounds Detected | – |
| Sensitivity/Selectivity | 100 ppt. |
| Measurement Time | Seconds. |
| Complexity of Use/ Training Requirements | Extensive training required. |
| Size and Portability of Equipment | Backpack. |
| Maturity | 1–5 years. |
| Affordability Issues | – |
| Safety Issues | – |
| Reliability/False Alarm | – |

BACKGROUND

CRDS uses an optical resonator with high reflectivity mirrors to measure vapor concentrations. Light is allowed to circulate in the cavity, and its decay rate is measured by monitoring light transmitted through the mirrors. The decay rate depends on the dimensions of the cavity, the reflectivity of the mirrors, and the concentration and absorbance cross section of the vapor sample. ERCs like TNT and 2,4 DNT have large absorbance cross section for certain wavelengths that can be detected with CRDS at sub ppb concentrations.

TECHNICAL ISSUES

- Limited selectivity: Current CRDS systems are limited to measuring one gas species.
- Measurements taken at higher pressures may lose sensitivity because of increased Rayleigh scattering.
- Interferences of other compounds can affect selectivity and sensitivity. Could produce false alarms.
- Device elements are bulky and expensive. Measurements may be sensitive to vibrations, limiting portability.

REFERENCES

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- Ramos, Christopher, and Paul J. Dagdigian. February 1, 2007. Detection of vapors of explosives and explosive-related compounds by ultraviolet cavity ring-down spectroscopy. *Appl. Opt.* 46(4): 620–627.

DATA SHEET B-8. CHEMICAL LUMINESCENCE

| | |
|---|--|
| Description of Technology | This technology detects infrared (IR) light from excited NO ₂ molecules. |
| Standalone Capability | Yes. Not ERC specific. With Gas Chromatography (GC) excellent. |
| Sample Collection Method | Vapors. |
| Compounds Detected | EGDN, NG,ANFO, TNT, DNT, RDX, PETN; problems with detecting non-nitrogen-based explosives. |
| Sensitivity/Selectivity | All nitrogen-based explosives plus detection taggants. ² |
| Measurement Time | Measurement time: seconds; refresh rate: seconds to minutes. |
| Complexity of Use/ Training Requirements | Relatively easy. |
| Size and Portability of Equipment | Man-portable, needs ultrapure carrier gas [argon (Ar) or helium (He)], which may limit operations. |
| Maturity | Available commercially. |
| Affordability Issues | 2 to 3 times as expensive as Ion Mobility Spectrometry (IMS). |
| Safety Issues | None. |
| Reliability/False Alarm | High rate of false alarms. |

BACKGROUND

Chemical luminescence, or chemiluminescence, is based on the detection of IR light emitted by electronically stimulated NO₂ molecules. By a chemical reaction, nitric oxide (NO) is produced from the compound and reacted with ozone to get the excited NO₂. The amount of light emitted is collected by a photomultiplier tube and red filter and is proportional to the amount of NO₂ and NO₃ inside the reaction chamber.

TECHNICAL ISSUES

As with most systems that are keyed to the nitrogen contained in explosives, chemical luminescence cannot distinguish between type of explosives nor explosive and nonexplosive nitrogen-containing compounds. It is used with a gas chromatograph front-end to help in selectivity but cannot detect non-nitrogen-containing explosives.

REFERENCES

Thermo Scientific commercial Web site: <http://www.thermo.com/>

² These are volatile chemicals that will slowly evaporate from the explosive and can be detected in the atmosphere by either dogs or specialized machines.

DATA SHEET B-9. ELECTRON CAPTURE DETECTION

| | |
|---|--|
| Description of Technology | Detects substances with high electron affinities through a change of standing current inside an Electron Capture Detector (ECD). |
| Standalone | – |
| Sample Collection Method | – |
| Compounds Detected | – |
| Sensitivity/Selectivity | 10–100 ppt 2,4 DNT (similar detection limit for TNT). |
| Measurement Time | Seconds. |
| Complexity of Use/ Training Requirements | – |
| Size and Portability of Equipment | Portable. |
| Maturity | Commercially available. |
| Affordability Issues | – |
| Safety Issues | – |
| Reliability/False Alarm | – |

BACKGROUND

Electron capture detection technology detects substances with high electron affinities through a change of standing current inside an ECD. Vapor is brought into the device and exposed to a radioactive source to gain electrons. The electrons are then thermalized and collected at an anode inside the ECD. The gas in the chamber is characterized by the standing current of electrons going to the anode, and explosives materials with high electron affinities lower this current.

TECHNICAL ISSUES

This technology cannot distinguish between compounds and is used with another type of detector (mainly GC) to identify explosives. Also, the ECD used for this technology has a radioactive source that poses regulatory problems.

DATA SHEET B-10. ELECTRON-CAPTURE DETECTOR (ECD)

| | |
|---|--|
| Description of Technology | The ECD is a device for use in gas chromatography (GC) that can detect tiny amounts of chemical compounds in the atmosphere. |
| Standalone Capability | No. Used with vapor collection systems ECD-equipped gas chromatographer. |
| Sample Collection Method | Vapor. |
| Compounds Detected | Species with high electron affinities. |
| Sensitivity/Selectivity | 1 ppb for electron-capturing compounds; 10 pg/ml [TCRP]; little discrimination between ERC and non-ERCs in standalone, often used with other detection methods (e.g., GC). |
| Measurement Time | Measurement time: seconds; refresh rate: seconds to minutes. |
| Complexity of Use/ Training Requirements | Easy |
| Size and Portability of Equipment | Man-portable; needs ultrapure carrier gas (Ar or He), which may limit operations. |
| Maturity | In university laboratories and also available commercially. |
| Affordability Issues | ~ \$20,000. |
| Safety Issues | Radioactive source. |
| Reliability/False Alarm | High rate of false alarms. |

BACKGROUND

“The ECD consists of a sealed stainless steel cylinder containing radioactive Nickel-63. The Nickel-63 emits beta particles (electrons) that collide with the carrier gas molecules, ionizing them in the process. This forms a stable cloud of free electrons in the ECD cell. When electro-negative compounds (especially chlorinated, fluorinated, or brominated molecules) such as carbon tetrachloride, bromoform, PCBs [polychlorinated biphenyls] and pesticides such as DDT [dichlorodiphenyltrichloroethane] enter the cell, they immediately combine with some of the free electrons, temporarily reducing the number remaining in the electron cloud. The detector electronics, which maintain a constant current (of about 1 nA) through the electron cloud, are forced to pulse at a faster rate to compensate for the decreased number of free electrons. The pulse rate is converted to an analog output which is connected to the data system. The SRI [Instruments] ECD detector can be operated with either nitrogen or argon/5% Methane (P5) makeup gas, and nitrogen, P5, or helium carrier as long as the helium flow is less than 10 ml/min.” (<http://www.srigc.com/catalog/ecddetector.htm>).

TECHNICAL ISSUES

- Requires ultra-purity carrier gas.
- Contamination of detection layer may occur after several uses, causing “ghost” peaks or broad humps in chromatogram.
- Selectivity is limited. Often remedied with the addition of a gas chromatograph stage.

DATA SHEET B-11. ELECTRONIC NOSE

| | |
|---|--|
| Description of Technology | An electronic nose is a device that identifies the specific components of an odor and analyzes its chemical makeup. To identify the odor, it uses a combination of chemical sensors and a pattern recognition algorithm. |
| Standalone Capability | No. |
| Sample Collection Method | A volume of air is passed through the sensor. |
| Compounds Detected | Depends on the selection of polymers. |
| Sensitivity/Selectivity | Not determined. |
| Measurement Time | – |
| Complexity of Use/ Training Requirements | – |
| Size and Portability of Equipment | Desktop and hand-held models exist. |
| Maturity | Commercially available |
| Affordability Issues | – |
| Safety Issues | – |
| Reliability/False Alarm | – |

BACKGROUND

The human nose has approximately 10,000 odor sensors that can be very sensitive to certain odors. It does not try to identify nor quantify the different constituents. Signals from human olfactory sensors are transmitted to the brain for processing. The brain then interprets what the sum of all these signals is describing in terms of odor. Today's electronic nose instruments attempt to do the same with many fewer sensors and a simulated brain consisting of a computer and sophisticated software.

Unlike chromatography techniques, the electronic nose does not attempt to separate or resolve all individual volatile components. Instead, it uses an array of sensors that responds to each volatile chemical in a slightly different way—much like the way the human nose functions. A set of polymers with different characteristics are mounted on a set of electrodes that act as sensors. If there is a change in the composition of the air, each polymer changes its size depending on the compound sensed, thus changing the effective resistance. The pattern of changes determines the particular compound sensed. A different compound would produce a different pattern of changes in the set of polymers used.

Presently, the three major manufacturers of commercial electronic nose instruments are Alpha M.O.S. (DeMotte, Indiana), AromaScan (Hollis, New Hampshire), and Neotronics (Gainesville, Georgia). While the instruments may look different, they have three primary functions that they perform in similar ways: data acquisition (detection of volatile flavor chemicals with specialized electronic sensors); data presentation [statistical graphic plots (e.g., polar plots, offset polar plots, bar charts, difference plots)]; and data interpretation (software to assist the user in understanding the practical significance of the graphical outputs, usually accomplished through applications of artificial neural networks).

TECHNICAL ISSUES

At this time, the electronic nose approach needs further development to detect reliably the very low equilibrium vapor concentrations of military explosives.

REFERENCES

Marsili, R. (Ed.). 1995. The electronic nose. *Food Product*, June edition,
<http://www.foodproductdesign.com/archive/1995/0695QA.html>

DATA SHEET B-12. GAS CHROMATOGRAPHY (GC)

| | |
|---|---|
| Description of Technology | A gas chromatograph is a chemical analysis instrument for separating chemicals in a complex sample. In this technique, gas flows over special beads in a column that interact more strongly with one chemical substance than others. The identification is made by the time rate of flow of different chemicals—detected and identified electronically. |
| Standalone Capability | Not good as standalone but used in many combinations [e.g., GC/chemiluminescence (CL), GC/ECD, GC/ion mobility spectrometry (IMS), GC/mass spectrometry (MS), GC/surface acoustic wave (SAW)]. |
| Sample Collection Method | Vapor. |
| Compounds Detected | – |
| Sensitivity/Selectivity | Picograms (manufacturer claim). |
| Measurement Time | Setup time: 10 min; measurement time: seconds to minutes. |
| Complexity of Use/ Training Requirements | Commercial systems – easy; laboratory systems – complex. |
| Size and Portability of Equipment | Briefcase-sized to laboratory-sized. |
| Maturity | Commercially available. |
| Affordability Issues | Depends on size and system. |
| Safety Issues | None. |
| Reliability/False Alarm | – |

BACKGROUND

GC is a well-known and mature laboratory technology for the detection of substances.

TECHNICAL ISSUES

Since GC is a mature technology, much focus has been on creating devices that can be used outside of the lab. Its popularity in being paired with other technologies comes from its nondestructive interrogation of chemical vapors, allowing the vapors to be used for subsequent testing by another device. Although great sensitivity and selectivity can be accomplished in the laboratory, it requires a lot of equipment and time to gain such results.

DATA SHEET B-13. ION MOBILITY SPECTROMETRY (IMS)

| | |
|---|---|
| Description of Technology | An air sample is ionized by a controlled radioactive material and allowed to enter a drift region where the mobility of the various ions in the sample is measured and used to classify the constituents of the sample. |
| Standalone | – |
| Sample Collection Method | – |
| Compounds Detected | – |
| Sensitivity/Selectivity | 10–1,000 ppt for TNT. |
| Measurement Time | 2–10 sec. |
| Complexity of Use/ Training Requirements | – |
| Size and Portability of Equipment | Portable. |
| Maturity | Commercially available. |
| Affordability Issues | – |
| Safety Issues | – |
| Reliability/False Alarm | – |

BACKGROUND

In IMS, an air sample is ionized in ambient conditions, and the mobility of the various ions is measured for detection. IMS devices commonly consist of two separated regions: ionization and drift. The ionization region is the first stage of the device and contains a small sealed piece of metal coated with a radioactive substance, commonly Nickel-63. Electrons from the source interact with the sample to form ions. These ions are admitted into the drift region, the second stage of the device, at certain time intervals by an electrically controlled shutter. The ions are collected on a Faraday plate, and the temporal plot of the resultant current is used to classify the ions of the sample. In the drift region, an electric field is applied that results in a net drift velocity of the ions at atmospheric pressure. The drift velocity is proportional to the field strength and depends on the mass, charge, cross section, and other aspects of the ion.

Other variations to the method described previously to perform ion mobility spectrums include field ion spectrometry and differential mobility spectrometry, but the principle is essentially the same. IMS does have difficulty resolving particles with similar mass/charge ratios. This problem is often remedied by including a gas chromatograph stage before the drift region to provide additional temporal spacing to similar species.

TECHNICAL ISSUES

- Calibration may be required when ambient pressure is not 1 atm.
- Peak resolution can be limited and may result in low selectivity for similar ERCs. Adding a gas chromatograph stage may increase selectivity, but the added stage will also increase analysis time.
- Warm up time can be nontrivial.
- Devices with higher sensitivities are generally larger.

REFERENCES

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- Haupt, Steven G., Shahed Rowshan, and William C. Sauntry. 2004. Volume 6: Applicability of portable explosive detection devices in transit environments. In TCRP Report 86, *Public transportation security*. Transportation Research Board. Washington, D.C.
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DATA SHEET B-14. LASER INDUCED BREAKDOWN SPECTROSCOPY (LIBS)

| | |
|---|---|
| Description of Technology | Nanosecond laser pulses are used to induce breakdown of a sample. The resulting plume is spectrally analyzed for emission spectra that characterize explosives. |
| Standalone | – |
| Sample Collection Method | – |
| Compounds Detected | – |
| Sensitivity/Selectivity | In the ppm to ppb range. |
| Measurement Time | Seconds. |
| Complexity of Use/ Training Requirements | – |
| Size and Portability of Equipment | Fieldable device has been built. |
| Maturity | 1–5 years. |
| Affordability Issues | – |
| Safety Issues | – |
| Reliability/False Alarm | – |

BACKGROUND

In LIBS, a nanosecond laser pulse is used to induce breakdown of a sample, and the emission spectra of the resulting laser plume is analyzed. The spectrum will contain emissions from ionic, atomic, and molecular species that were produced during the breakdown. Explosive detection is performed by either comparing the spectrum to a library of experimentally obtained spectra or examining the intensity ratio of the nitrogen and oxygen emission peaks. The wavelengths of interests fall between 240 and 260 nm.

TECHNICAL ISSUES

- Different soil types may result in different background spectra. Calibration may be required.
- Since a sample area's emission spectrum is changed after laser-induced breakdown, a sample area cannot be tested more than once. A spatial averaging technique may be needed for detection purposes.

REFERENCES

Delucia, F. C., Jr., A. C. Samuels, R. S. Harmon, R. A. Walters, K. L. McNesby, A. LaPointe, R. J. Winkel, Jr., and A. W. Miziolek. August 2005. Laser-induced breakdown spectroscopy (LIBS): A promising versatile chemical sensor technology for hazardous material detection. *IEEE Sensors Journal* 5(4): 681–689.

DATA SHEET B-15. MASS SPECTROMETRY (MS)

| | |
|---|---|
| Description of Technology | A device that separates ions by use of magnetic fields and measures their mass-to-charge ratio. |
| Standalone Capability | Not good as a standalone. Must use with other sensors. |
| Sample Collection Method | Vapor, particulate. |
| Compounds Detected | Any molecule with unique mass-to-charge ratio. |
| Sensitivity/Selectivity | Approximately picogram (pg) range and low ppb. Laboratory devices have excellent specificity. |
| Measurement Time | Minutes. |
| Complexity of Use/ Training Requirements | Complex for laboratory; easy for commercial. |
| Size and Portability of Equipment | Need high-vacuum system; portable systems available. |
| Maturity | Basic MS science well understood. |
| Affordability Issues | Expensive, ~ \$70,000. |
| Safety Issues | None. |
| Reliability/False Alarm | Very reliable. |

BACKGROUND

MS is a mature and well-known technology for the laboratory analysis of materials. However, it has only been recent that MS devices for outside the laboratory have been developed. These devices have not been primarily designed to detect explosive materials but, rather, other environment hazards.

TECHNICAL ISSUES

MS uses magnetic fields and ionizing fields to determine the identity of molecules since most molecules have a unique mass-to-charge ratio.

DATA SHEET B-16. OPTICAL SENSOR ARRAY (OSA)

| | |
|---|--|
| Description of Technology | A large number of polymer and/or dye-treated silica beads are deposited on the distal end of a fiber-optic cable. A charge-coupled device (CCD) camera detector monitors florescent changes in the microsensors caused by the presence of analyte molecules. |
| Standalone | – |
| Sample Collection Method | – |
| Compounds Detected | – |
| Sensitivity/Selectivity | 23 ppb 2,4 DNT; 80 ppb 1,3 DNB. |
| Measurement Time | 5 sec. |
| Complexity of Use/ Training Requirements | – |
| Size and Portability of Equipment | A field-deployable cart has been built. Can be engineered into a smaller device. The CCD camera will be the limiting size component. |
| Maturity | Improvement in sensitivity should be near term. |
| Affordability Issues | – |
| Safety Issues | – |
| Reliability/False Alarm | More field tests are required. |

BACKGROUND

The OSA contains a large number of microsensor beads with diameters on the order of micrometers placed in small wells on the end of a fiber optic cable. The beads can be a mix of specific and nonspecific microsensors. Nitroaromatic compound (NAC)-specific microsensors are commonly polymer-based beads with electron-donating groups that attract electron-accepting NACs. Nonspecific microsensors are commonly silica beads coated with different types of dyes, which exhibit changes in emission and excitation behavior because of changes in their micro-environments. The time-dependent florescent response of these sensors to vapor pulses is dependent on vapor compositions and has been shown to show particular shapes for particular analytes.

For the detection of NACs, a CCD camera monitors the florescent response of the sensors in the array and compares the resulting pattern to patterns previously established to be associated with particular NACs. The large number of sensors in the array serves to increase the signal-to-noise ratio (SNR), which potentially increases the sensitivity of the sensor array.

TECHNICAL ISSUES

- The pre-established NAC patterns must be calibrated on the field to account for temperature and humidity changes. This requires spiking the ground with an NAC and establishing a pattern from that sample.

REFERENCES

- Albert, Keith J., and David R. Walt. 2000. High-speed fluorescence detection of explosives-like vapors. *Anal. Chem.* 72(9): 1947–1955.
- Albert, Keith J., M. L. Myrick, Steve B. Brown, Dale L. James, Fred P. Milanovich, and David R. Walt. 2001. Field-deployable sniffer for 2,4-Dinitrotoluene detection. *Environ. Sci. Technol.* 35(15): 3193–3200.

Dickinson, Todd A., Karri L. Michael, John S. Kauer, and David R. Walt. 1999. Convergent, self-encoded bead sensor arrays in the design of an artificial nose. *Anal. Chem.* 71(11): 2192–2198.

DATA SHEET B-17. PHOTOACOUSTIC SPECTROSCOPY (PAS)

| | |
|---|---|
| Description of Technology | Gas atoms absorb light of a specific wavelength and then vibrate, producing a measurable acoustic signal. |
| Standalone Capability | Yes. |
| Sample Collection Method | Vapor. |
| Compounds Detected | TNT, EGDN, NG, DNT, PETN. |
| Sensitivity/Selectivity | Sub ppm. |
| Measurement Time | Minutes. |
| Complexity of Use/ Training Requirements | Complex. |
| Size and Portability of Equipment | – |
| Maturity | Unknown. |
| Affordability Issues | – |
| Safety Issues | None. |
| Reliability/False Alarm | – |

BACKGROUND

When molecules in the air absorb energy from a laser beam, they heat up. If the laser beam is pulsed repetitively, the molecules alternately heat and cool. The cycle of heating and cooling produces an acoustic wave that can be detected by a microphone and amplified electronically. The intensity of the sound wave is directly proportional to the concentration of molecules absorbing energy.

Jaycor, a research and development (R&D) company based in San Diego, is developing a device, based on this well-known principle, for detecting narcotics, explosives, and hazardous chemicals. As of this time, no more information can be found on this project. Although some papers were found on this technology, they dated back to 1978.

TECHNICAL ISSUES

The system requires a laser and from previous papers, a laboratory setup.

REFERENCES

- Haisch, C., and Niessner, R. 2002. Light and sound—photoacoustic spectroscopy. *Spectroscopy Europe* 14(5): 10, 12, 14–15.
- Patel, C.K.N., E.G. Burkhardt, and C.A. Lambert. 1974. Spectroscopic measurements of stratospheric nitric oxide and water vapor. *Science* 184:1173–1176.

DATA SHEET B-18. POLYMER FLUORESCENCE

| | |
|---|---|
| Description of Technology | New lasing polymer creates large increases in explosives detection sensitivity when coupled to a general method for amplified chemical sensing. Can be used for military and civilian security applications. The novel semiconducting organic polymer (SOP) when exposed to ultraviolet (UV) light undergoes a stimulated emission or a lasing process. When TNT is present, it binds to the SOP surface and quenches the beam. |
| Standalone | – |
| Sample Collection Method | – |
| Compounds Detected | – |
| Sensitivity/Selectivity | 6 ppt TNT. |
| Measurement Time | 5 sec. |
| Complexity of Use/ Training Requirements | – |
| Size and Portability of Equipment | A field-deployable cart has been built and can be engineered into a smaller device. The CCD camera will be the limiting size component. |
| Maturity | Improvement in sensitivity should be near term. |
| Affordability Issues | – |
| Safety Issues | – |
| Reliability/False Alarm | More field tests are required. |

BACKGROUND

Amplifying fluorescent polymers (AFPs) link many chromophores³ in a “molecular wire.” When a linked chromophore comes into contact with the analyte of interest, all linked chromophores undergo a change in fluorescence (i.e., they quench). Amplified fluorescence polymer swager uses a polymer that greatly increases the sensitivity of chemical detections systems for TNT. The polymer undergoes a lasing action at lower operating powers than previous polymers. The stimulated light emission from the lasing modes of the polymer display high sensitivities to explosive vapors. The semiconducting organic polymer provides even greater sensitivity to polymer sensitive detection of explosive compounds. When exposed to UV light above a certain threshold, the semiconducting organic polymer material begins a lasing process. When TNT is present, the TNT binds to the semiconducting organic polymer surface and quenches the beam.

TECHNICAL ISSUES

- At this time, amplified fluorescent polymer has only been reported for TNT. It is expected that polymers specific for other nitroaromatic explosive compounds will be developed.
- Improvement in sensitivity.
- Scaled down design for portability.

³ A chromophore is part of a molecule responsible for its color. When a molecule absorbs certain wavelengths of visible light and transmits or reflects others, the molecule has a color. A chromophore is a region in a molecule where the energy difference between two different molecular orbitals falls within the range of the visible spectrum. Visible light that hits the chromophore can thus be absorbed by exciting an electron from its ground state into an excited state.

REFERENCES

- Aimée, Rose, Larry Takiff, Kristen Mulherin, Matthew Garret, Timothy Swager, Zhengguo Zhu, Vladimir Bulovic, Conor Madigan, Ofer Shapira, Fabien Sorin, and Yoel Fink. 2006. Advances in vapor-phase explosives detection. Paper presented at the 25th Army Science Conference: Transformational Army Science & Technology—Charting the Future of S&T for the Soldier, Orlando, FL, November 27–30.
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- Moore, D. S. Instrumentation for trace detection of high explosives. August 2004. *Review of Scientific Instruments* 75(8): 2499–2512.

DATA SHEET B-19. PRECONCENTRATORS

| | |
|---|---|
| Description of Technology | Used to increase the concentration of vapors in collection and detection systems. |
| Standalone Capability | No. Used with vapor collection systems. |
| Sample Collection Method | Vapors. |
| Compounds Detected | – |
| Sensitivity | – |
| Measurement Time | – |
| Complexity of Use/ Training Requirements | Easy. |
| Size and Portability of Equipment | Hand-held and man-portable. |
| Maturity | In university laboratories and available commercially. |
| Affordability Issues | – |
| Safety Issues | – |
| Reliability/False Alarm | – |

BACKGROUND

Preconcentrators increase the amount of target material reaching a detector by filtering air and collecting target material to be sent directly to the detector. Two types of systems are (1) vapor sampling, which relies on an increase in air flow, and (2) swipe sampling, which uses air flow and heating to increase the concentration of material in vapor form.

TECHNICAL ISSUES

This is a technology used with many other forms of vapor detection devices to increase their sensitivity. Depending on the type of system, vapor or swipe, the increase in the concentration of material will vary but will be at least an order of magnitude greater.

REFERENCES

- German, John. August 13, 1999. Miniaturization of chemical preconcentrators brings better bomb-detecting and drug-sniffing devices. *Sandia Lab News* 51(16).
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DATA SHEET B-20. RESONANTLY ENHANCED MULTIPHOTON IONIZATION (REMPI)

| | |
|---|---|
| Description of Technology | The inlet cools the molecules to some 20 K. A laser is tuned to a resonance transition, which is excited by one laser photon. Absorption of a second photon produces the parent ion. This is then detected by MS. |
| Standalone | – |
| Sample Collection Method | – |
| Compounds Detected | – |
| Sensitivity/Selectivity | In the ppt range. |
| Measurement Time | Seconds. |
| Complexity of Use/ Training Requirements | – |
| Size and Portability of Equipment | In lab use. Not portable. |
| Maturity | 5–10 years. |
| Affordability Issues | – |
| Safety Issues | – |
| Reliability/False Alarm | – |

BACKGROUND

REMPI is a technique applied to the spectroscopy of atoms and small molecules. In practice, a tunable laser can be used to access an excited intermediate state. The selection rules associated with a two-photon or other multiphoton photoabsorption are different from the selection rules for a single photon transition. The REMPI technique typically involves a resonant single or multiple photon absorption to an electronically excited intermediate state followed by another photon which ionizes the atom or molecule. The light intensity to achieve a typical multiphoton transition is generally significantly larger than the light intensity to achieve a single photon photoabsorption. Because of this, a subsequent photoabsorption is often very likely. An ion and a free electron will result if the photons have imparted enough energy to exceed the ionization threshold energy of the system. In many cases, REMPI provides spectroscopic information that can be unavailable to single photon spectroscopic methods, for example rotational structure in molecules is easily seen with this technique.

Jet-REMPI is a method comprising a supersonic nozzle inlet, a tunable laser, and a time-of-flight (TOF) mass spectrometer. It offers many significant advantages over other vapor detection approaches, including exceptional sensitivity and chemical specificity, both achieved while operating as a real-time, continuous mode.

TECHNICAL ISSUES

- Photo fragmentation of samples has proven to be a problem. Research is moving toward single photon ionization to remedy this problem.
- The jet-cooling system requires complex parts. Research is looking at non-jet-cooled sampling.
- Photo ionization currently requires complicated optics.

REFERENCES

Spicer, J. et al. 2005. Approaches to trace explosives detection in condensed and vapor phases. Paper presented at the ARO MURI 2005.

DATA SHEET B-21. REVERSAL ELECTRON ATTACHMENT

| | |
|---|---|
| Description of Technology | A system slows down electrons so that they can efficiently attach to high-affinity electronegative groups, producing both negative or positive ions that are detected by a mass analyzer. |
| Standalone Capability | Yes. |
| Sample Collection Method | – |
| Compounds Detected | NO ₂ . |
| Sensitivity/Selectivity | – |
| Measurement Time | < seconds. |
| Complexity of Use/ Training Requirements | – |
| Size and Portability of Equipment | Small and portable. |
| Maturity | Mature; used in laboratory. |
| Affordability Issues | < \$20,000. |
| Safety Issues | None. |
| Reliability/False Alarm | – |

BACKGROUND

Compounds with highly electronegative groups, such as the NO₂ in explosives or the halogens in chlorofluorocarbons, have high affinities for electrons. When electrons at very low energies (less than 10 MeV) hit such compounds, the electrons attach efficiently, causing the compound to form a characteristic anion or to dissociate in a unique pattern. Electrons with very low energies are produced by firing electrons into an electrostatic “mirror,” which acts like a brake, reducing the electrons to zero or near-zero kinetic energies and then sending them back.

A high-current ionizer capable of focusing a beam of electrons on a test region and executing a reversal of the electrons, such that the electrons possess zero kinetic energy at the point of reversal, can be used to produce negative and positive ions. A sample gas is introduced at the point of electron reversal for low-energy electron (sample gas)/molecule attachment with high efficiency. The attachment process produces negative ions from the sample gas, which includes species present in trace (minute) amounts. These ions are extracted efficiently and directed to a mass analyzer, where they can be detected and identified. The generation and detection of positive ions is accomplished in a similar fashion, with minimal adjustment to potentials applied to the apparatus.

A detector based on this principle is part of a system being developed by the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) to help the Navy find UXO and mines in bays and harbors.

TECHNICAL ISSUES

- Efficient extraction of ions for analysis.
- Compact design for portability

REFERENCES

Boumsellek, S., and A. Chutjian. 1992. Increased response of the reversal electron attachment detector and modeling of ion space-charge effects. *Anal. Chem.* 64(18): 2096-2100.

Boumsellek, S., S. H. Alajajian, and A. Chutjian A. March 1992. Negative-ion formation in the explosives RDX, PETN, and TNT by using the reversal electron attachment detection technique. *J. Am. Soc. Mass Spectrom.* 3(3): 243–247.

Reversal electron attachment ionizer for detection of trace species United States Patent 4933551

<http://www.freepatentsonline.com/4933551.html>

DATA SHEET B-22. SURFACE ACOUSTIC WAVE (SAW)

| | |
|---|---|
| Description of Technology | A layer of antibodies on surface of piezoelectric crystal selectively attracts and adsorbs explosive molecules. A transmitter sends acoustic surface waves that are detected by a receiver. Mass of adsorbed molecules perturbs frequency of waves This change can be detected and identifies the explosive molecule. |
| Standalone Capability | – |
| Sample Collection Method | – |
| Compounds Detected | – |
| Sensitivity/Selectivity | In the ppb range for explosive molecules; less than 10^{-9} grams of material per cm^2 detected. |
| Measurement Time | Seconds to minutes. |
| Complexity of Use/ Training Requirements | – |
| Size and Portability of Equipment | Hand-carried. |
| Maturity | Sensor mature but needs to be tested in field. |
| Affordability Issues | \$10,000. |
| Safety Issues | – |
| Reliability/False Alarm | Sensor needs to be tested in field. |

BACKGROUND

The basis of the SAW technique is the piezoelectric effect in crystals discovered by Jacques and Pierre Curie in 1880. They found that pressure exerted on certain crystals (e.g., quartz, tourmaline, and rochelle salt) produces an electric potential across the crystal. The inverse effect is used in the SAW technique. A time-varying electric signal on the surface of a piezoelectric crystal produces SAWs that can be detected by a sensor. Most of the early work was devoted to producing high-resolution filters. However, it was discovered that if the surface is coated to adsorb certain molecules selectively, the SAW can be used as a sensitive sensor for that molecule. A monomolecular layer is enough coverage for detection, but, often, several layers are used.

In 1957, G. Sauerbrey derived the relationship between mass and frequency when foreign layers are deposited on thickness-shear mode crystals. The Sauerbrey equation assumes a uniform distribution of mass on the entire electroded portion of the crystal, but experiments show that the sensitivity to mass changes from the center of the crystal to the electrodes.

TECHNICAL ISSUES

- Control of the number of layers deposited
- Specificity to explosive molecules depends on the existence of appropriate antibody layer.

Counter or Disabling Technology

- Tighter, well-encased mines
- Cleaner mine surfaces.

REFERENCES

Drafts, B. October 2000. Acoustic wave technology sensors. *Sensors* 17(10).
<http://archives.sensorsmag.com/articles/1000/68/index.htm>

DATA SHEET B-23. SURFACE PLASMON RESONANCE (SPR)

| | |
|---|--|
| Description of Technology | Immobilized antibodies attached to the surface of an SPR device are exposed to antigens that can potentially bond to the antibodies and to the specific analytes and the targeted sample. Decreases in antigen-antibody bonding because of analyte presence in the sample result in smaller resonance angle changes in the SPR sensor. |
| Standalone Capability | – |
| Sample Collection Method | – |
| Compounds Detected | – |
| Sensitivity/Selectivity | 60 ppt–1000 ppb for TNT. |
| Measurement Time | 10–20 min. (does not include sample preparation). |
| Complexity of Use/ Training Requirements | – |
| Size and Portability of Equipment | No size information, but technology does not appear to be portable. |
| Maturity | Near to current availability for lab testing of soil samples; mid-term availability for fast, portable, in-the-field implementations. |
| Affordability Issues | – |
| Safety Issues | – |
| Reliability/False Alarm | More field tests required. |

BACKGROUND

Common surface plasmon resonance sensors consist of a metal [commonly Gold (Au)] annealed to the flat edge of a half-circular prism. For such a device, total internal reflection (TIR) of incident light occurs for all incident angles. For particular frequencies and angles of incident light on the prism, photons are absorbed by the metal layer and are converted into surface plasmons, resulting in a drop in the reflected intensity. For constant frequency, the angle at which this resonance occurs is often called the resonance angle. The conditions necessary for this resonance effect depend on the thickness of the metal layer and the refractive indices of the prism and the medium above the metal layer. Therefore, changes in the refractive index of the medium above the metal layer will result in a change in the resonant angle that can be measured precisely.

For trace explosive detection, particular antibodies are immobilized on the surface of the metal layer. The bonding of antibodies to analytes will result in a change in the refractive index of the layer and, therefore, a change in the resonant angle. However, direct detection of TNT and other nitroaromatic molecules through bonding to the antibody layer will result in very small signal because of low concentrations and small molecular weight. A preferred method of TNT detection makes use of the principle of indirect competitive immunoreaction. In this method, antigens are created that can potentially bond to the antibodies or the TNT molecules. These antigens are mixed with the sample and placed in the sensor. When no TNT is present in the sample, the antigens are expected to saturate the antibody layer and give a baseline resonance angle change. When TNT is present in the sample, the TNT will bond with some of the antigens and decrease the amount of antigens available to bond to the antibody layer. This decrease can be detected by a decreased change in resonance angle compared to the baseline case.

TECHNICAL ISSUES

- Soil samples must be prepared thoroughly before measurement.
- The sensor must be calibrated with a neutral, clean sample before testing.

REFERENCES

- Shankaran, Dhesingh R., K. Vengatajalabathy. Gobi, Takatoshi Sakai, Kiyoshi Matsumoto, Toshihiko Imato, Kiyoshi Toko, and Norio Miura. 2005. A novel surface plasmon resonance immunosensor for 2,4,6-trinitrotoluene (TNT) based on indirect competitive immunoreaction: A promising approach for on-site land mine detection," *IEEE Sensors Journal* 5(4): 616–621.
- Strong, Anita K., Donald I. Simpson, Dwight U. Bartholomew, Thomas F. Jenkins, and Jerome L. Elkind. August 1999. Detection of trinitrotoluene (TNT) extracted from soil using a surface plasmon resonance (SPR)-based sensor platform. In Proceedings of SPIE, Volume 3710, *Detection and remediation technologies for mines and minelike targets V*, eds. Abinash C. Dubey, James F. Harvey, J. Thomas Broach, and Regina E. Dugan, 362–372.

DATA SHEET B-24. TERAHERTZ SPECTROSCOPY

| | |
|---|--|
| Description of Technology | The reflected and transmitted spectrum from a terahertz source can be used to detect the presence of explosives. Also, terahertz radiation can be used to penetrate soil and detect bulk explosives. |
| Standalone Capability | – |
| Sample Collection Method | – |
| Compounds Detected | – |
| Sensitivity/Selectivity | – |
| Measurement Time | – |
| Complexity of Use/ Training Requirements | – |
| Size and Portability of Equipment | In lab use. Not portable. |
| Maturity | 5–10 years. |
| Affordability Issues | – |
| Safety Issues | – |
| Reliability/False Alarm | – |

BACKGROUND

Materials of interest, such as explosives and chemical agents, have characteristic spectra in the terahertz range, and common nonmetallic materials are practically transparent to terahertz radiation. For these reasons, the reflected and transmitted spectra of a target from a terahertz source can be used to detect the presence of explosives.

TECHNICAL ISSUES

- Terahertz spectra of explosive compounds can be sensitive to sample preparation and geometry. This can affect selectivity.
- For trace detection, the transmission mode is optimal, which requires a two-sided detection device.
- The sensitivity of a terahertz system has not been determined.
- Sources of terahertz radiation currently require femto-second pulse lasers and nonlinear optical elements.
- For bulk detection, soil can strongly attenuate terahertz signals. A terahertz system may require a large power source for detection of nonmetallic objects.

REFERENCES

Federici, John F., Brian Schulkin, Feng Huang, Robert Barat, Filipe Oliveria, and David Zimdars. 2005. THz imaging and sensing for security applications—explosives, weapons, and drugs. *Semicond. Sci. Technol.* 20(7): S266–S280.

DATA SHEET B-25. THERMO-REDOX (TR) DETECTORS

| | |
|---|--|
| Description of Technology | TR detector heats a sample to release NO ₂ molecules, which are sensed using an electrochemical detector. |
| Standalone Capability | No. Used with vapor collection systems. |
| Sample Collection Method | Vapors. |
| Compounds Detected | Any nitroaromatic compound. |
| Sensitivity/Selectivity | Moderate; cannot detect RDX and PETN because vapor pressure is too low. A lot of potential interferents. |
| Measurement Time | Measurement time: seconds. refresh rate: seconds to minutes. |
| Complexity of Use/ Training Requirements | Easy. |
| Size and Portability of Equipment | Hand-held. |
| Maturity | In university laboratories and available commercially. |
| Affordability Issues | ~ \$20,000–\$23,000. |
| Safety Issues | None. |
| Reliability/False Alarm | High because of number of interferents (NO ₂ -containing compounds). |

BACKGROUND

Based on the thermal decomposition of explosive molecules and the reduction of NO₂ groups present in those compounds, TR technology detects the NO₂ molecules released during this process.

A TR detector is similar to the chemiluminescence detector. It is basically used for the detection of explosives since it works only with nitrogen-rich materials. Air is flowed into a series of capillary tubes coated with catalytic material. The capillary tubes are heated to a very high temperature. Chemical vapors from the explosive materials are broken down and a by-product of this process is NO₂. A group of sensors capable of detecting NO₂ is located at the outlet of the capillary tubes. The signals from the NO₂ sensors are proportional to the amount of chemical vapor from high explosives present.

TECHNICAL ISSUES

TR only detects the presence of NO₂. It can not distinguish between explosives and nonexplosives that contain those molecules. It is used with other detection technology to distinguish between such substances. It cannot detect explosives that do not contain NO₂ groups.

REFERENCES

Haupt, Steven G., Shahed Rowshan, and Willaim C. Sauntry. 2004. Volume 6: Applicability of portable explosive detection devices in transit environments. In TCRP Report 86, *Public transportation security*. Transportation Research Board. Washington, D.C.
<http://cms.transportation.org/sites/scopt/docs/Public%20Transportation%20Security%20VOL%206.pdf>

APPENDIX C.

RADIATION BULK EXPLOSIVE DETECTION TECHNOLOGIES

| Data Sheet | Page |
|--|-------------|
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| C-8. X-Ray Backscatter | C-10 |

DATA SHEET C-1. FAST NEUTRON ANALYSIS (FNA)

| | |
|--|---|
| Description of Technology | FNA techniques measure the results of the reaction of fast neutrons with suspect matters (e.g., elastic scattering and production of characteristics gamma rays). The neutron energy has to be above a given threshold for each of the elements involved. The intensity of gamma rays indicates the relative amount of materials present. It is, therefore, in principle, possible to calculate the elements ratios (i.e., how much of each element is present with respect to the others) to determine the type of substance under analysis. |
| Sensitivity | – |
| Measurement Time | Minutes. |
| Size and Portability of Equipment | Vehicle-mounted. |
| Maturity | Sensor mature but needs to be tested in field. |
| Affordability Issues | \$100,000. |
| Reliability/False Alarm | – |

BACKGROUND

Neutron detection technologies generally irradiate the ground with neutrons and measure scattered or emitted neutrons or emitted photons. Both collimated and uncollimated beams are used. FNA measures the characteristic γ -rays as a result of interaction of fast neutrons with matter, for example inelastic scattering interactions of the type $(n,n'\gamma)$ and the resulting emission of characteristic γ -rays:

- Carbon (4.43 MeV)
- Oxygen (6.13, 3.84 MeV)
- Nitrogen (1.63, 2.3, 5.1 MeV)
- Hydrogen cannot be determined by pure FNA.

Soil above the mine absorbs neutrons, but the extent is location dependant.

TECHNICAL ISSUES

Need to determine sensitivity under different environmental conditions.

DATA SHEET C-2. GAMMA-NEUTRON REACTION TECHNOLOGY

| | |
|--|---|
| Description of Technology | A 10-MeV gamma ray absorbed by nitrogen produces Nitrogen-14, which is a positron emitter. Positron annihilates an electron emitting two oppositely emitted γ -rays of 511 keV each. Detection of these γ -rays signals the presence of nitrogen. |
| Sensitivity | – |
| Measurement Time | Seconds to minutes. |
| Size and Portability of Equipment | – |
| Maturity | Sensor mature but needs to be tested in field. |
| Affordability Issues | \$100,000 |
| Reliability/False Alarm | – |

BACKGROUND

At 10 MeV of gamma ray energy, nitrogen undergoes a reaction $^{14}\text{N}(\gamma, n)^{13}\text{N}$. This reaction peaks at 16 MeV and falls to minimum at 25 MeV. The product ^{13}N is a positron emitter with a half life of 10 min and no gamma rays emitted. Positron annihilates an electron emitting two oppositely emitted γ -rays of 511 keV each. Detection of these γ -rays signals presence of nitrogen.

TECHNICAL ISSUES

Need to determine sensitivity under different environmental conditions.

DATA SHEET C-3. MINEBUSTER TECHNOLOGY

| | |
|--|---|
| Description of Technology | Neutrons are produced in self-colliding plasma through the d+B reaction. The fast neutrons (6 MeV to 8 MeV) react with nitrogen and other elements producing high-energy gamma rays that provide the explosive signature. |
| Sensitivity | – |
| Measurement Time | Minutes. |
| Size and Portability of Equipment | Vehicle-mounted. |
| Maturity | Sensor mature but needs to be tested in field. |
| Affordability Issues | \$100,000. |
| Reliability/False Alarm | – |

BACKGROUND

Neutron detection technologies generally irradiate the ground with neutrons and measure emitted photons. Both collimated and uncollimated beams are used. In the Minebuster approach, fast neutrons (6 MeV to 8 MeV) react with nitrogen and other elements with the result that

- The $^{14}\text{N}(n,n'\gamma)^{14}\text{N}$ reaction produces a 4.1 MeV gamma ray.
- Neutrons undergo many other reactions with soil and explosives.

For 4.1 MeV, a quasi-triple coincidence is needed for a “TRUE” event to be registered. Background reduction can be high (10^6 or more). Carbon and common soil elements also produce ~ 4.1 MeV gamma rays. The “Double Differential” analysis technique is used: (a) neutron energy is varied, (b) derivative of 4.1 MeV gamma intensity is calculated, and (c) peak in derivative spectrum occurs if nitrogen is present.

Soil above the mine absorbs neutrons but the extent is location dependant.

TECHNICAL ISSUES

Need to determine sensitivity under different environmental conditions.

REFERENCES

Harris, Daniel C., and Michael D. Bertolucci. 1989. *Symmetry and spectroscopy: An introduction to vibrational and electronic spectroscopy*. New York: Dover Publication.

DATA SHEET C-4. NUCLEAR QUADRUPOLE RESONANCE (NQR)

| | |
|--|--|
| Description of Technology | A technique which uses radio frequency (RF) pulses to excite NQR transitions and detects the emitted responses to identify explosives. NQR lines are characteristic of a chemical and thus provide a specific fingerprint for the explosive of interest. Different pulses are needed to excite resonances in different explosives. The important parameters in determining the signal strength and the repetition rate are the number of inequivalent sites in a compound and the relaxation rate. |
| Sensitivity | <p>Hand-held detectors used to confirm that sensors can detect explosives 3 in. to 10 in. deep, depending on the type [antipersonnel (AP) or antitank (AT)] or the weight of the explosive. Since the signal cannot penetrate a metal casing, metallic mines cannot be identified by the chemical present inside but do destroy the impedance match, thus providing some useful information.</p> <p>In principle, NQR provides signals only in the presence of bulk quantities of the explosive. The false alarm rate is not driven by ground clutter but by the signal-to-noise ratio (SNR), which increases linearly with the mass of the explosive and goes as the square root of the interrogation time.</p> |
| Measurement Time | Seconds to minutes at each spot, depending on the explosive present. |
| Size and Portability of Equipment | Hand-carried systems, including ground-penetrating radar (GPR) and metal detectors, have been tested. Vehicle-mounted NQR systems also exist. |
| Maturity | This technology has been developed and tested in the field. |
| Affordability Issues | — |
| Reliability/False Alarm | Sensor needs to be tested in field. |

BACKGROUND

A nucleus orients in the electric field gradient of the electron charge distribution. Transitions between different orientations produce emissions that can be detected by an antenna. These emissions are characteristic signatures of the nuclear-electronic system and can be used to identify explosives. This is similar to nuclear magnetic resonance (NMR) except that the interaction, which is the basis of the phenomena, is between an electric field gradient and the nuclear quadrupole moment instead of the nuclear spin and the magnetic field, as in NMR. This effect, NQR (nuclear quadrupole resonance), is sometimes referred to as zero field NMR. For identifying explosives, the nitrogen isotope is used.

TECHNICAL ISSUES

- Interference of RF signals from radio stations with the explosive signal.
- Interference from induced signal in silicon crystals in soil.

Counter or Disabling Technology

- Metal-encased mines.

DATA SHEET C-5. PULSED FAST-NEUTRON ANALYSIS (PFNA)

| | |
|--|--|
| Description of Technology | PFNA provides timing information (coincidence and anticoincidence measurements) as well as the characteristic gamma ray signature produced in FNA. Timing information is useful for background reduction and three dimensional (3-D) spatial resolution. |
| Sensitivity | – |
| Measurement Time | Minutes. |
| Size and Portability of Equipment | Vehicle-mounted. |
| Maturity | Sensor mature but needs to be tested in field. |
| Affordability Issues | \$100,000. |
| Reliability/False Alarm | – |

BACKGROUND

Neutron detection technologies generally irradiate the ground with neutrons and measure scattered or emitted neutrons or emitted photons. Both collimated and uncollimated beams are used. PFNA, as with FNA, measures the result of interaction of fast neutrons with matter [e.g., inelastic scattering interactions of the type $(n,n'\gamma)$ and the resulting emission of characteristic γ -rays]. However, in addition, PFNA has the capability to provide timing information (coincidence and anticoincidence measurements), background reduction, and a 3-D spatial resolution. Mono energetic beams fast electronics are needed for optimum results.

- Carbon (4.43 MeV)
- Oxygen (6.13, 3.84 MeV)
- Nitrogen (1.63, 2.3, 5.1 MeV)
- Hydrogen cannot be determined by pure FNA.

Soil above the mine absorbs neutrons, but the extent is location dependant.

TECHNICAL ISSUES

Need to determine sensitivity under different environmental conditions.

DATA SHEET C-6. RAMAN SPECTROSCOPY

| | |
|--|--|
| Description of Technology | Lasers are used to radiate explosive solids or vapors. Most photons are elastically scattered (Rayleigh scattering) and have the same frequency as the incident photons. A small fraction of the scattered light is scattered at optical frequencies different from that of the incident beam. The spectrum of this smaller fraction of scattered light corresponds to the rotation and vibration spectrum of the target material. |
| Sensitivity | RDX, TNT |
| Measurement Time | < 1 sec |
| Size and Portability of Equipment | Small Business Innovation Research (SBIR) grants are awarded for developing instruments for field use. |
| Maturity | Commercial laboratory instruments. Fieldable prototypes being developed. |
| Affordability Issues | None. |
| Reliability/False Alarm | — |

BACKGROUND

In 1922 Chandrasekhara Venkata Raman (1888–1970), an Indian physicist, published *Molecular Diffraction of Light*. Raman received the Nobel Prize in 1930 for his work on the scattering of light and for his discovery of what would come to be called the Raman effect. The Raman effect describes the absorption and subsequent emission of a photon via an intermediate electron state. The differences in energy between incident and emitted frequencies are dependent only on the energy of the different vibrational levels of the target molecule.

TECHNICAL ISSUES

The distortion of an explosive molecule in an electric field is determined by the material's polarizability. A Raman transition occurs only when the polarizability of the explosive molecule changes during vibration or rotation.

REFERENCES

- Harris, Daniel C., and Michael D. Bertolucci. 1989. *Symmetry and spectroscopy: An introduction to vibrational and electronic spectroscopy*. New York: Dover Publication.
- Herzberg, Gerhard. 1950. *Spectra of diatomic molecules*. New York: D. Van Nostrand Co.

DATA SHEET C-7. THERMAL NEUTRON ANALYSIS (TNA)

| | |
|--|---|
| Description of Technology | This technique depends on the ability to characterize explosives by their nitrogen and hydrogen content using thermal neutron capture followed by emission of a 10.835 gamma. Isotopic sources have been used but neutron generators have also been proposed. |
| Sensitivity | – |
| Measurement Time | Minutes to tens of minutes. |
| Size and Portability of Equipment | Vehicle-mounted. |
| Maturity | Sensor mature and tested in field; projected improvements with higher resolution γ-ray detectors. |
| Affordability Issues | \$100,000. |
| Reliability/False alarm | As confirmation sensor: (a) Probability of Detection 0.95; false alarm rate 15%: low soil absorption of neutrons (Socorro, New Mexico, site) (b) Probability of Detection 0.55; false alarm rate 15%: high soil absorption of neutrons (Yuma, Arizona, site). |

BACKGROUND

Neutron detection technologies generally irradiate the ground with neutrons and measure scattered or emitted neutrons or emitted photons. Both collimated and uncollimated beams are used. In TNA, a thermal neutron (~ 0.025 eV) interacts with a Nitrogen-14 nucleus, and, when the neutron is captured, a 10.835-MeV gamma is emitted. The emission of the gamma indicates a nitrogen presence and together with the hydrogen signature (a 2.223 MeV gamma) is the signal for the presence of bulk explosive. The dependability of the test result depends on the SNR and the presence of other sources of nitrogen, which contribute to the false alarm rate.

Soil above the mine absorbs neutrons but the extent is location dependant.

TECHNICAL ISSUES

Need to determine sensitivity under different environmental conditions.

DATA SHEET C-8. X-RAY BACKSCATTER

| | |
|--|---|
| Description of Technology | X-rays scatter from matter and can be detected, producing images of density variations in the areas of interest. Since mines and soils have different mass densities and effective atomic numbers, they can be discriminated. |
| Sensitivity | – |
| Measurement Time | Interrogation time is 1m ² per minute. |
| Size and Portability of Equipment | System weight ~ 100 kg; size 1 m ³ ; rugged for field use but heavy to carry. |
| Maturity | Sensor mature but needs to be tested in field. |
| Affordability Issues | \$100,000. |
| Reliability/False Alarm | – |

BACKGROUND

High-energy radiation emitted by electrons is referred to as X-rays, and that emitted by the nuclei is called gamma-rays. X-rays are produced when an electron makes a transition from a higher state to a lower state. The photon energy is the difference between the energies of the upper and lower states and is usually given in terms of electron Volts (eV) ($1 \text{ eV} = 1.6 \times 10^{-19}$ Joule, the energy acquired by an electron when accelerated by a potential of 1 Volt). The absorption of an X-ray beam decays exponentially in materials with the exponent given by the product of μ [the mass attenuation coefficient (g/cm^2)], l [the length of the path (in cm)] and ρ [the density of the absorbing medium (g/cm^3)].

The absorption in the medium is due to interaction with the electrons: (a) photoelectric effect, (b) Compton effect and at high energies (greater than 1.022 MeV), and (c) pair production.

For explosives detection, there are basically two approaches. One uses collimated beams and collimated detectors. The other uses uncollimated beams to irradiate a broad area and then uses a spatial filter to determine the location of the scattering points. In both methods, 60- to 100-keV incident photons are used. In this energy range, cross sections are about an order of magnitude larger than for other nuclear reactions of possible use, and the shielding requirements are reduced. Thanks to the developments in the medical imaging field, compact X-ray generators are available.

When the mines are encased in plastic, the situation is even better. Since low-Z (i.e., low atomic number) materials are more efficient at scattering X-rays, explosive materials stand out clearly in the backscatter image.

TECHNICAL ISSUES

Need to determine sensitivity under different environmental conditions. Sensor mine depth limitation: in lab 8 cm; in field 5 cm.

| REPORT DOCUMENTATION PAGE | | | Form Approved OMB No. 0704-0188 | |
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| Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS. | | | | |
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| 14. ABSTRACT Most military and commercial detectors sense the presence of metal casings or components of buried mines or explosive ordnance; however, this traditional approach to mine and unexploded ordnance (UXO) detection is prone to high false alarm rates. Explosive components, common to all mines and ordnance devices, offer a unique discriminator among buried objects. Two approaches to detect buried explosive devices directly are investigated: chemical trace detection, which relies on detecting either the vapor emanating from buried devices or the small explosive particles [and/or their explosive-related compounds (ERCs)] concentrated in the top soil, and radiation techniques, which uses radiation to probe beneath the earth's surface to provide bulk detection of buried explosive devices. This report describes the technology approaches and the current performance of each approach and discusses some promising new explosive detection technologies. It suggests that the Joint Unexploded Ordnance Coordination Office (JUXOCO) take a leadership role in establishing standards and protocols for reporting the results of field measurements in which trace analyses are used for detection of buried mines and ordnance and in sponsoring the development and maintenance of an open-sourced code to predict the variability of explosive detection in different environments. | | | | |
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